ADAPTIVE USE OF CROP GROWTH MODELS TO SIMULATE THE GROWTH OF FIELD-GROWN TOMATO

By

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Dedicated in loving memory to my mother Eve, who has always been very supportive of me during my stay overseas. She stimulated me in my growth and development as a human being, but unfortunately could not enjoy the fruits of her hard work.

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By

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Major Department: Soil and Water Science

The objective of this work was to compare actual and model-predicted growth and fruit yield of field-grown tomato (Lycopersicon esculentum Mill.) under a range of production conditions. Reduced water and nitrogen (N) supply typically resulted in an appreciable reduction of leaf area and light interception. Severe N-stress resulted in a reduction in N concentration of the leaves, while leaf number, average leaf size, and specific leaf area were also decreased. Water and N stress also reduced photosynthetic rates and radiation use efficiency, but these reductions were relatively small compared to the reduction in light interception. Following a detailed literature analysis, it was concluded that the water use efficiency (WUE) for tomato was on the order of 0.2 t fresh-fruit weight per mm of irrigation water. With the use of tensiometer-controlled systems, this value was doubled. Based on the results of a field experiment it was concluded that

water stress during initial vegetative growth resulted in a reduction in canopy size. However, increased soil moisture depletion at greater soil depths resulted in relatively high fruit yields. Water stress during fruit development, on the other hand, only reduced fruit yield. Total root length increased from 3 m at transplanting to 1500 to 3000 m per plant at harvest, with most roots being confined to the upper 15 to 30 cm of the soil profile. Fruit weight increased linearly with time and maximum fruit size was attained 38-45 physiological days after anthesis. Yield reductions due to N and water stress were closely related to the corresponding reductions in light interception and fruit number. Fruit dry matter percentage followed an exponential decay, and decreased from approximately 12% at anthesis to 5% at fruit maturation. As N-rates increased from 0 to 330 kg N ha^{-1}, N accumulation by tomato plants increased from 20 to 330 kg N ha^{-1} while N uptake by the fruit was typically on the order of 100 kg N ha^{-1}. Apparent N recovery rates were on the order of 0.95 and 0.70 for subirrigated and drip-irrigated crops, respectively. N recovery rates decreased as N rates increased. With the use of the TOMGRO model, effects of nutrient and water stress on plant growth were not accounted for. Modifying crop parameters resulted in a close match between predicted and actual vegetative growth patterns; however, fruit yields were greatly under-predicted. With the use of the CROPGRO model it proved feasible to capture growth characteristics typical of field-grown tomato by modifying existing parameter files previously used for peanut (Arachis hypogea L.). In its current form, the CROPGRO model is well-calibrated for field-grown tomato, and the model should provide potential users with reasonably accurate yield predictions under near-optimal conditions.

CHAPTER 1
INTRODUCTION

Tomato is one of most important vegetable crops in the world, with a world-wide fresh fruit production of about 40 million tons and a total acreage of approximately 2 million ha (Doorenbos and Kassam, 1986). The crop is grown over a wide range of climates, in production systems ranging from smallholder subsistence farming in Africa to computer-controlled greenhouse production in Western Europe. Fresh fruit yields for these production systems are on the order of 1-5 t ha^{-1} and 200-300 t ha^{-1}, respectively.

In Florida, 23,000 ha of tomato are grown annually, with a total yield of 730 x 10^6 Mt and a crop value of $461 million (Florida Agricultural Statistics Service, 1996). The crop is typically grown on flatwoods sites, using raised mulched production beds, and plants are typically both well-irrigated and well-fertilized. The most commonly used irrigation systems are drip and subsurface (seepage) irrigation, with commercial fertilizer rates on the order of 300-400 kg N ha^{-1} (McNeal et al., 1995). Average marketable fruit yields are on the order of 40 ton ha^{-1} but, under optimal conditions, yields in excess of 100 t ha^{-1} may be possible. More stringent environmental regulations, along with increased competition with other production regions, create a favorable environment for the use of expert systems to assist growers in more efficient water and nutrient use. The use of expert systems may also assist producers to 1) evaluate production practices that will meet federal regulations and 2) target more profitable market windows.

The development of dynamic crop-growth models during the last few decades has resulted in a number of models that allow the simulation of plant growth under well-defined environmental conditions. These models can provide inputs to management decisions for commercial crops like peanut (Boote et al., 1989) and tomato (Jones et al., 1989a). However, the use of existing growth models to predict the growth and production of fresh-market tomato requires some modifications, since each of the existing models was developed for different crops, cultivars, and production systems.

The purpose of this study is to describe general growth characteristics of tomato plants and to adapt the TOMGRO (Jones et al., 1989a) and CROPGRO (Hoogenboom et al., 1992; Scholberg, 1994) crop growth models to allow the simulation of plant growth of field-grown tomato under well-defined environmental conditions. Specific objectives of this dissertation are to:

1. Provide information on the general growth characteristics of field-grown tomato under near-optimal conditions;

2. Describe the effects of water- and nutrient-stress on plant growth and development;

3. Adapt the CROPGRO and TOMGRO crop-growth models for field-grown tomato;

4. Outline some of the more important modifications to crop- and cultivar-specific parameters of these models in order to adequately describe tomato plant growth;

5. Assemble a data base for crop growth under well-defined climatic, geographic, and management conditions to enable the continued development, calibration, and validation of the respective models;

6. Outline functional relationships that will describe fruit size; fruit dry matter content; and fresh fruit weight over time; and

7. Describe nutrient and root distribution in mulched production beds over time.

CHAPTER 2
LITERATURE REVIEW

Introduction

Tomato belongs to the family of the Solanaceae, which also includes a number of other vegetable crops (potato, eggplant, and pepper), a number of ornamental crops, and some toxic species (Solanum nigrum and Atropa belladonna). Varieties used for commercial tomato production (*Lycopersicon esculentum* Mill.) evolved from the cherry tomato (*L. Esculentum* var. *cerasiforme*) which originated from the Peru-Ecuador region. Tomato was first brought to Spain by explorers returning from South America, and from there it found its way to Italy (Peirce, 1987). The first documentation of its use dates back to 1544, when it was referred to as pomi d'oro (golden apple). Subsequently it was named poma amoris (love apple), with its current name being derived from the Native American word "tomatl" (Varga and Bruinsma, 1986). It was introduced in the United States in 1710, but its initial use was limited due to the popular belief that the fruits were poisonous like the fruits of other species in the nightshade family (Peirce, 1987).

Economic Importance of Tomato Production

Since its introduction, tomato has become one of the most important vegetable crops and is extensively cultivated throughout the world (Table 2-1). The total

area under tomato production in the United States in 1992 amounted to 164,000 ha, of which 53,000 ha was planted to fresh-market tomato (National Agricultural Statistics Service, 1993). Per capita consumption of tomato in the United States during 1994 amounted to 33.1 and 7.3 kg per capita per year (farm weight basis) for processing and fresh-market tomato, respectively (Commodity Research Bureau, 1995). Tomato production in Florida and California accounted for 54% and 24% of the total fresh market production for the United States, respectively (Table 2-2). The area under tomato production in Florida annually amounts to about 20,000 ha, with approximately 12,500 and 7,500 ha being planted to spring and fall crops, respectively (Florida Agricultural

Table 2-1. Overview of tomato production for various regions of the world for 1994[1]

Region	Area harvested (1000 Ha)	Yield (t ha^{-1})	Production (1000 MT)
Africa	428	19.4	8,315
N. and C. America	326	45.7	14,874
S. America	157	34.0	5,335
Asia	1182	23.2	27,430
Europe	402	38.6	15,537
Oceania	10	40.3	433
USSR	406	18.1	7,371

[1] Fresh-market and processing tomato combined, FAO 1994 production yearbook

Table 2-2. Overview of fresh-market tomato production in the United States for 1992 [1]

State	Area harvested (1000 Ha)	Yield (t ha^{-1})	Production (1000 MT)	Total crop value (10^6 dollars)
Florida	20.0 (38.1)[2]	44.3	885.9 (54.2)	786.4 (60.3)
California	15.0 (28.5)	26.7	399.5 (24.4)	299.2 (22.9)
Virginia	1.3 (2.5)	46.0	59.6 (3.6)	40.7 (3.1)
S.Carolina	1.5 (2.9)	31.4	48.3 (3.0)	22.5 (1.7)
Georgia	0.9 (1.9)	40.9	39.8 (2.4)	29.9 (2.3)
Tennessee	1.8 (3.5)	17.9	32.7 (2.0)	15.1 (1.2)
Pennsylvania	1.7 (3.2)	19.1	32.4 (2.0)	15.1 (1.2)
New Jersey	1.9 (3.7)	14.0	27.2 (1.7)	21.4 (1.6)
Ohio	1.2 (2.3)	16.8	20.4 (1.3)	14.0 (1.1)
Other	7.0 (13.4)	12.6	88.6 (5.4)	60.1 (4.6)
Total U.S.	52.5 (100)	31.1	1634 (100)	1304 (100)

[1] National Agricultural Statistics Service, 1993; [2] Values in parentheses indicate percentages

Statistics Service, 1996). The average fresh-market tomato yield is on the order of 40 t ha^{-1}, with the major production areas and production per region in Florida being outlined in Table 2-3. The area under tomato production increased from 17,100 ha (in 1979) to 25,300 ha in 1989, after which it declined to 19,800 ha in 1994 (Fig. 2-1). The average price of tomato increased from $5.23 per carton (1979) to $9.40 per carton (1990), but

Table 2-3. Overview of the major tomato production regions in Florida for 1994[1]

Region		Area harvested (1000 Ha)	Yield ($t\ ha^{-1}$)	Production (1000 MT)
I	Dade (Florida City, Goulds, Homestead, Perrine)	2.07 (10.3)	44.3	78.1 (10.4)
II	East Coast (Ft. Pierce, Jupiter, Osceola County, Pompano Beach, Stuart)	2.47 (12.3)	42.5	104.9 (13.9)
III	Southwest (Bonita Springs, Immokalee, Naples)	8.71 (43.3)	32.0	279.0 (37.0)
IV	Palmetto-Ruskin (Palmetto, Ruskin, Tampa)	5.18 (25.8)	43.0	222.7 (29.5)
V	North (Oxford, Suwannee Valley) and West (Gadsen, Holmes, and Jackson counties)	1.66 (8.3)	41.8	69.5 (10.4)

[1] Florida Agricultural Statistic Service, 1995

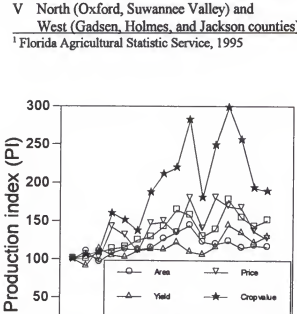


Fig. 2-1. Production trends, fresh-market tomato production, Florida (Area: PI_{100} = 17,000 ha; Yield: PI_{100}= 31 t ha^{-1} ; Total Production: PI_{100}= 527 * 10^6 MT; Price: PI_{100} = $5.23 $carton^{-1}$; Crop value: PI_{100}= $244 * 10^6).

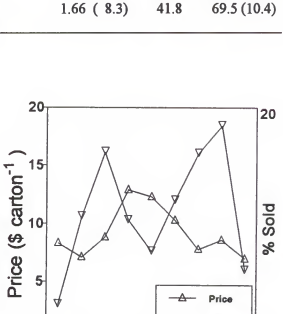


Fig. 2-2. Seasonal production trends, fresh market production, Florida (average values for the 1989 to 1994 production seasons)

price fluctuations between years and within years were appreciable (Figs. 2-1 and 2-2). Overall price fluctuations in the last 10 years ranged from $3.93 (December 1988) to $29.00 (January 1990), and average monthly prices from 1989 through 1994 varied between $7.06 in June and $12.97 in January (Fig 2-2). Tomato production in Florida increased until the late eighties, but current production appears to be decreasing (Fig 2-1). Reduction in total production revenues are related to a general price decrease over the last five years, along with unfavorable weather conditions which have resulted in yield reductions (Florida Agricultural Statistics, 1995). The estimated production costs for tomato are on the order of $10,200-$11,400 per acre, with operating, fixed and harvesting costs accounting for roughly 33%, 19%, and 48% of the total production costs, respectively (Appendix A, Table 1). The cost of fertilizer typically accounts for only 2.3-3.4% of total production costs. Excessively high fertilizer rates are thus commonly used as inexpensive "insurance premiums" to prevent yield losses under poor weather or water management conditions. Estimated returns for tomato production in Florida vary greatly and depend on tomato price and tomato yield (Fig. 2-3). Net returns for average yields may range from -$1821 per acre to $3779 per acre as the market price increases from $6 per carton to $10

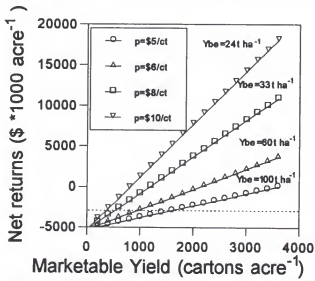


Fig 2-3. Estimated returns and break-even crop yields (Ybe) for a spring tomato crop for Manatee County, Florida.

per carton. Production levels required to meet production costs (Y_{be}) increase from 24 t ha^{-1} to 100 t ha^{-1} if tomato prices drop from $10 per carton to $5 per carton (Fig 2-3).

Growth and Development

Root Growth

Tomato plants are characterized by their ability to adapt their root systems to a wide range of soil conditions. Tomato root systems are highly branched and may extend to a soil depth of 26 to 267 cm, depending on the location of a confining soil layer and the water table (Portas and Dordio, 1980). The pattern of root development is genetically controlled but may be modified by environmental factors (Pitts et al., 1991). The use of plastic mulch enhances lateral root growth, and lateral spreading of the root system typically increases from 15 cm to 45 cm and then to 75 cm at 6, 20, and 42 days after transplanting, respectively (Portas and Dordio, 1980; Wien et al., 1987). Frequent irrigation may be conducive to the formation of a shallow root system, whereas drought stress may enhance root development to greater soil depth (Dirks and Tan, 1988; Giardini et al., 1988a). With the use of drip irrigation, root proliferation is most pronounced in the vicinity of the emitter (Bar-Yosef et al., 1980), while the use of subirrigation may confine rooting to the well-aerated zone above the water table (Tan, 1988).

Root expansion rates for tomato range from 0.7 cm day^{-1} during early spring to 4.3-8.6 cm day^{-1} under optimal growth conditions (Gasim and Hurd, 1986; Portas and Dordio, 1980). The root system may extend to a depth of 100 cm within 6 weeks after

transplanting (Tan and Fulton, 1985). Generally, 60-95% of the total root mass and 40-45% of the total root length are located in the top 20-30 cm of the soil profile, while 45% of the total water uptake may occur from the top 30 cm (Bar-Yosef et al., 1980; Giardini et al.,1988a; Sanders et al., 1989b). Root density for tomato is very high in the top 20 cm of soil after which it declines sharply, which may be related to the "breaking" of the tap-root commonly observed for transplanted tomato (Portas and Dordio, 1980). Root densities at greater soil depths are much lower for tomato compared to corn, while the uptake capacity per unit root length appears to be higher for tomato (Portas and Dordio, 1980; Tan and Fulton, 1985). Root length densities in the top 30 cm of soil for tomato typically range from 0.5-20 cm cm^{-3} depending on the soil location, soil strength, soil moisture, N and O_2 concentrations of the soil atmosphere (Bar-Yosef et al., 1980; Clark et al., 1989; Sanders et al., 1989). The average radius of tomato roots is on the order of 0.1 mm and 4.3 μm for roots and root hairs, respectively, but root hairs may account for as much as 70% of the total surface area for young tomato plants (Barber and Silverbush, 1984). Reported values of total root length per plant range from 400 to 2,500 m per plant (Portas and Dordio, 1980; Richards et al., 1979). Reported root length per gram of root weight range from 10-40 m g^{-1} dry weight of secondary and tertiary roots (Gulmon and Turner, 1978; Jackson and Bloom, 1990).

Dry matter allocation to the roots is on the order of 30% during initial vegetative growth, is reduced to 15-20% during flowering, and decreases to 3-8% during fruit development (Jackson and Bloom 1990; Ruff et al., 1987; Scholberg, 1994). Maximum development of the root system occurs 6-8 weeks after transplanting, after which

increased senescence and remobilization of assimilates can at times result in reduction of total root mass (Bar-Yosef and Sagiv, 1982). Typical values for total root weight for field-grown tomato in production beds of Florida range from 4-6 g plant^{-1} (Stoffela, 1983) to 20 g plant^{-1} (McNeal et al., 1995). Jackson and Bloom (1990), however, reported values on the order of 100 g plant^{-1} for production systems in California with a deep water table. The relatively low values reported for Florida may be attributed to shallow and fluctuating water tables, which may enhance root respiration, root sloughing, and root die-back (Smuckers, 1984).

Plant Growth and Photosynthesis

Based on plant growth characteristics, tomato plants can be classified as indeterminate, semi-determinate, or determinate. These plant types are most commonly used for greenhouse production, fresh-market field crop production, and the processing industry, respectively. Tomato is a day-neutral crop with a growing period of 90 to 150 days for determinate and semi-determinate types and up to a year for indeterminate varieties. The optimal daily temperatures for growth range from 21 to 29 °C, with corresponding optimum night temperatures between 18 and 20 °C (Doorenbos and Kassam, 1986; Peirce, 1987). For indeterminate types the apical bud continues to grow, resulting in a vining growth-pattern type. For determinate types, each stem ends in a flower cluster, and axillary shoots develop more readily. This results in short and bushy plants. Semi-determinate plants are inherently determinate in nature but form a larger

number of fruit clusters before forming a terminal fruit cluster, resulting in tall and bushy plants. They typically require both pruning and staking (Peirce, 1987).

Tomato leaves are odd-pinnately compound with seven to nine larger leaflets, and a variable number of smaller leaflets. Leaves are usually arranged around the stem in a spiral with a 2/5 phyllotaxy (Varga and Bruinsma, 1986). Leaf size depends on leaf position and age, with maximum leaf size ranging from 400 to 1000 cm^2 (Jones et al., 1989b; Tanaka et al., 1974). During initial development, the leaf imports assimilates via the phloem but photosynthetic capacity rapidly develops as leaf size increases and the leaf becomes a net exporter of assimilates instead (Ho and Hewitt, 1986). For greenhouse tomato maximum rates of leaf photosynthesis are on the order of 25-35 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ and photosynthetic rates are positively correlated with specific leaf area (SLA) and with leaf contents of N, P, and chlorophyll (Acock et al., 1978; Jones et al., 1989b; Tanaka et al., 1974). Dry matter content and the SLA of leaves increase as they mature, while photosynthetic rates decrease with aging of the leaves or if leaves become shaded by other leaves (Acock et al., 1978; Tanaka et al, 1974). The canopy photosynthetic rate for a greenhouse crop with a leaf area index (LAI) of five is on the order of 40-45 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ (Acock et al., 1974; Jones et al., 1989b). Nitrogen stress can result in reduced chlorophyll content of the leaves, leaf thickening, a decrease in leaf area, and a reduction in photosynthesis by up to 40% (Motta and Medina, 1978). Water stress results in a decrease in stomatal conductance and photosynthesis of as much as 45%, but normal photosynthetic rates are reportedly restored two weeks after rewatering (Tan et al., 1981).

The phloem network of a tomato plant consists of internal and external phloem

which are mainly associated with upward and downward movement of assimilates, respectively. As leaves mature the export of assimilates to other plant organs increases. Mature leaves export 45-50% of the carbon fixed, within a period of 48 hours. Carbon export rate appears to be closely related to the rate of carbon fixation (Ho, 1975; Ho and Hewitt, 1986). During reproductive growth, most of this assimilate pool is exported to the fruit and is accumulated in tomato fruits within 3 hours after fixation (Ho and Hewitt, 1986).

The effect of sink demand on photosynthesis in tomato is much smaller than for crops like soybean and wheat. Removal of fruit clusters will reduce carbon export from leaves within 1-3 days, while the rate of photosynthesis may only be affected after two weeks (Ho et al., 1983). Reduction in sink demand of the fruit results in increased partitioning of assimilates to stems and petioles and accumulation of starch and sucrose in the leaf (Ho et al., 1983). When carbon supply to the fruit is reduced due to leaf shading or senescence, remobilization of carbon stored in stems and roots may also occur (Ho and Hewitt, 1986). Biomass accumulation over time depends on relative growth rate, growth duration, and the rate of crop senescence. The relative growth rate for tomato is on the order of 0.16-0.29 g g^{-1} d^{-1}, with reported values for the net assimilation rate (NAR) being on the order of 18 g d^{-1} m^{-2} (Motto and Medina, 1978; Nicola and Basoccu, 1994; Ruff et al., 1987).

Little effort has been made to conduct comprehensive studies on the photosynthesis and vegetative growth of field-grown tomato, with only fruit yield typically being measured when evaluating new varieties and production practices. Plant growth

with subsurface irrigation is typically more vigorous than with drip irrigation, which could be related to high supply of N-fertilizer during initial growth and ample supply of water for subirrigated production systems. A well-managed, subirrigated, tomato crop may have a LAI of 5.5-6.5, a total dry matter production of 9-12 ton ha^{-1}, and a total marketable fruit yield of 80-120 t ha^{-1}. The development of canopy leaf area and accumulation of biomass typically follows a sigmoidal curve characterized by a lag phase ($t < 42$ days) and a linear growth phase (42 days $< t <$ 70 days), followed by a period when total biomass approaches its maximum ($t > 84$ days) and PAR use efficiency is reduced once more due to increased leaf senescence (Challa and Heuvelink, 1993; Hsiao, 1990; Marlowe et al., 1983; Scholberg, 1994). Biomass production during the lag phase is limited due to incomplete light interception by the canopy, while biomass accumulation is limited by radiation during the linear growth phase (Hsiao, 1990). Jones (1979) reported that continuous removal of 30-40% of the foliage of a tomato crop did not result in significant yield reductions, while canopy reductions up to 10-20% may actually result in a yield increase.

Fruit Development

Flowering of tomato starts after the formation of 6-12 nodes and occurs 3-5 weeks after transplanting, depending on temperatures and transplant size (Scholberg, 1994). Flower clusters contain 4-12 flowers, with each flower consisting of a five-lobed corolla and calyx. The fusion of the anthers around the style and stigma favors self-pollination, which occurs as flowers vibrate from wind currents. The tomato fruit is a berry without a

rind, and fruits have two or more cavities (locules) surrounded by the pericarp. The seeds are embedded in a gelatinous matrix of placental tissue that softens as the fruit reaches maturity. Before and shortly after pollination fruit growth occurs through cell division; thereafter, fruit cells become vacuolated and fruit size increases mainly due to cell expansion (Varga and Bruinsma, 1986).

Generally fruit yield is not determined by total flower number but by fruit-set percentage and the rate of fruit development. The critical factor in fruit setting is night temperature, with temperatures above 30 °C often causing stigma exertion, cone splitting, and poor pollen growth, thereby reducing fruit set (Varga and Bruinsma, 1986). Temperatures below 10° C may also impair fruit set, while temperatures above 32 ° C along with high humidity and low radiation levels may cause excessive vegetative growth and delay or reduce fruit production (Doorenbos and Kassam, 1986; Peirce, 1987).

Accumulation of dry matter by the fruit is controlled by both sink size and sink activity (Hewitt et al., 1982). One week after anthesis, fruit development is internally controlled by the number of fruit seeds, and fruit size is reportedly proportional to the logarithm of the seed number while fruit development rate is inversely proportional to seed number (Varga and Bruinsma, 1986). A seed number below 8-10 results in inadequate sink capacity of the fruit and, as a result, the fruit will not pass the parthenocarpic size, which corresponds to a fresh fruit weight of about 30 to 50 g (Varga and Bruinsma, 1986). The accumulation of dry matter in proximal fruits is typically greater than that in distal fruits, which is related to higher cell numbers of the ovary and higher IAA levels in proximal fruits. Accumulation of assimilates in proximal fruits is not greatly affected by

reduced assimilate supply, while distal fruits have their highest growth rates during the period of declining assimilate use by proximal fruits (Ho et al., 1983; Ho and Hewitt, 1986).

At flowering each fruit is mainly supplied by the two leaves just below it while, during fruit development, it may receive additional assimilates from the leaves above it as well. Fruits contain chlorophyll but the net photosynthetic rate is only 0.064 mg CO_2 g fw^{-1} h^{-1}, so more than 90% of the fruit dry matter is imported from leaves through the phloem (Ho and Hewitt, 1986). Due to the larger size of older leaves and the relatively small diameter of the external phloem, the subtended leaves are usually the principal suppliers of assimilates to the fruit (Ho and Hewitt, 1986). The import rate of assimilates is determined by the sink strength of the fruit rather than by the actual photosynthetic rate of the source leaves, however, while dry matter content and final fruit size are mostly controlled by irradiance level (Ho, 1988; Ho and Hewitt, 1986; Johnson et al., 1992).

Fruit development is externally controlled by light, temperature, relative humidity, CO_2 concentration and the supply of both water and nutrients. Extended periods of low irradiancy result in increased flower abortion, while increasing ambient CO_2 concentrations result in an increase in both fruit number and fruit weight (Ho, 1988; Ho and Hewitt, 1986). At low temperatures fruit development is reduced due to decreased assimilate transport from the leaves, reduced nutrient uptake by the roots, and decreased rates of starch synthesis and respiration in the fruit. At low temperatures, the partitioning of assimilates to the roots and stems is also increased, though translocation rates of assimilates are reduced (Ho and Hewitt, 1986). High temperatures increase the growth

rates and respiration rates of fruits, with the increase in assimilate demand often reducing vegetative growth and delaying the growth of newly set fruit (Koning, 1989a). The import of H_2O by the fruit peaks out at four weeks after anthesis with a peak value on the order of 3-4 g fruit^{-1} d^{-1}, while transpiration rates are highest for mature fruits with levels of 0.8-1.0 g fruit^{-1} d^{-1} (Ho et al., 1987). Water stress reduces fruit size and also may result in a shorter fruit-growth period. A reduction in water potential of the stem below -1.1 to -1.5 MPa may result in apoplasmic efflux of water from the fruit (Ho and Hewitt, 1986; Lee, 1989).

Dry matter partitioning to fruits increases from 1-5% during initial flowering to 40-75% during fruit development (Ruff et al., 1987; Scholberg 1994) with the cumulative increase in fruit weight generally following a sigmoidal growth pattern. Absolute growth rates reach a maximum value of 2-3 g d^{-1} four weeks after anthesis, while relative growth rates peak one week after anthesis with values on the order of 0.8 g g^{-1} d^{-1} (Varga and Bruinsma, 1986). The rate of respiration is highest two weeks after anthesis (0.4-0.6 mg CO_2 g fw^{-1} h^{-1}), and lowest at fruit maturation (0.05-0.07 mg CO_2 g fw^{-1} h^{-1}), but increases again during fruit ripening (0.1-0.14 mg CO_2 g fw^{-1} h^{-1}). The dry matter content of the fruit decreases from 17% prior to fertilization to 8% one week after anthesis, and finally reaches a value of 5-6% at fruit maturation (Ho and Hewitt, 1986; Lacheene and El-Beltagy, 1986). Moderate water stress has a pronounced effect on water uptake by the fruit, though only a relatively small effect on dry matter accumulation by the fruit (Adams and El-Gizawy, 1986; Mitchell et al., 1991). Moderate water and salinity

stress can increase dry matter content of the fruit and may also enhance fruit quality and fruit ripening (Ho, 1988).

Carbon content of the fruit remains fairly constant throughout its entire development, at approximately 39%. Although sucrose is the principal imported assimilate, its concentration in the fruit remains low and glucose and fructose are the principal fruit sugars. They account for about half of the dry matter at fruit maturation. The rate of starch accumulation in the fruit has a pronounced effect on final soluble solids content of the fruit, with the rate of starch accumulation being highest 20 days after anthesis. This results in a maximum starch content of about 20%, at 25-30 days after anthesis. Starch content at fruit ripening is only 1%, however. Citric and malic acid are the most common organic acids in the fruit, accounting for 13% of the dry matter (Ho and Hewitt, 1986). During fruit development N and P contents are reduced from 3% and 0.6% to 2% and 0.4%, respectively, while K content of the fruit remains fairly constant at levels of 3-4% (Ho and Hewitt, 1986).

With incipient ripening the chlorophyll content of the fruit decreases, with color development related to the formation of lycopene (red) and β-carotene (orange). High temperatures favor the development of β-carotene, resulting in a more orange hue (Peirce, 1987). In Florida, fruits are typically harvested at the mature green stage in order to reduce losses during shipping and handling (Hochmuth, 1988). An overview of the ripening and size classes used during commercial production in both Florida and the United States is presented in Appendix A, Tables 2 and 3. Fruit production per plant for well-managed, high-yielding, varieties may range from 6-10 kg for field crops to 13-14 kg

for greenhouse crops. Respective plant populations are on the order of 12,000 and 25,000 plants ha^{-1}, production cycles typically average 3-4 and 9-12 months, and harvest indices are on the order of 64-68% and 56-60%, respectively (Challa and Heuvelink, 1993; Ho and Hewitt, 1986; Scholberg, 1994).

Crop Production

Production Systems

Tomato production has evolved from a simple system where berries were collected from their natural habitat to highly sophisticated and specialized management systems (Appendix A, Table 4). As production systems evolved over time, producers tended to become more specialized and were also able to exert more control over the physical production environment. This resulted in higher yields and increased input use (Appendix A, Table 1). As a result, plants are typically grown during time periods when rainfall, radiation, and temperature normally would be unfavorable for successful production. Currently, environmental regulations, price fluctuations and competition with other production regions are among the key factors controlling commercial tomato production.

Field spacing of tomato depends on growth characteristics of the cultivar and on the production system. Semi-determinate tomato typically requires staking and planting in single rows 1.2-1.8 m apart, with plants generally 0.45-0.90 m apart in the row. This results in plant densities ranging from 6000-12,000 plants ha^{-1} (Hochmuth, 1988; Marlowe et al., 1983). Determinate plants (processing tomato) are commonly direct-seeded in

either single or double rows, resulting in higher plant densities (14,800-34,600 plants ha^{-1}) while, for fresh-market production, transplants are commonly used (Peirce, 1987). Fruit yield typically increases quadratically with increasing plant population, with optimal plant density depending on canopy characteristics and upon the specific production system (Bryan et al., 1967; Nassar, 1986). Typically, transplants are 4-6 weeks old and 10-15 cm tall, with 3-5 nodes, a leaf area of 15-30 cm^2, and a dry weight of 0.20-0.25 g (Scholberg, 1994).

Cultivars may differ in growth characteristics; disease resistance; fruit size, color, shape, and quality; and adaptation to unfavorable conditions (Peirce, 1987). Agriset is currently the most commonly used tomato variety in Florida, followed by Sunny and Solarset. In 1994 , 41, 18 and 9% of the total production area was planted with these varieties, respectively (Florida Agricultural Statistics, 1995). Sunny is relatively less sensitive to unfavorable growing conditions (T. McBride 1996, personal communication), while Solarset performs better at high temperatures.

The use of plastic mulch may enhance crop growth, fruit yield, and fruit quality (Wien et al., 1987). It also facilitates weed control and reduces water and nutrient loss from the production beds (Hochmuth, 1988). Pruning of the lower axillary shoots increases fruit size but heavy pruning may reduce total yield, however (Olson, 1989).

Irrigation

The total water requirement (Et_m) after transplanting for a field-grown tomato crop is on the order of 400-600 mm, depending on climate and the length of the

production season. Tomato is moderately sensitive to salinity stress and fairly sensitive to drought. The effects of water stress on relative yield of a tomato crop can be quantified using the equation

$$(1 - \frac{Y_a}{Y_m}) = ky\ (1 - \frac{ET_a}{ET_m}) \qquad (1)$$

where: Y_a = actual yield, Y_m = maximum yield, ky = yield response factor, ET_a = actual evapotranspiration, and ET_m = maximum evapotranspiration. For tomato the overall value of ky is 1.05, but the crop is most sensitive to water stress just after transplanting, at flowering and during early fruit development (Doorenbos and Kassam, 1986). Values of ET_m can be derived from the equation

$$ET_m = k_c.ET_o \qquad (2)$$

where K_c is the crop coefficient and ET_o is the evapotranspiration by a reference crop. Values of K_c may range from 0.2-0.5 to 0.9-1.15 during initial vegetative growth and fruit development, respectively (Maynard and Hochmuth, 1995). Values of ET_o may be derived from empirical relations (e.g., the Penman approach) or by measuring evaporation from a class A evaporation pan (E_{pan}) as follows:

$$ET_o = k_{pan}.E_{pan} \qquad (3)$$

where k_p is the pan factor, which averages approximately 0.8 under climate conditions typical for Florida.

For fresh-market tomato production, the best fruit quality and yields are obtained by using light, frequent irrigations, well-distributed over the growing period. Soil water should be kept above 60% of available water capacity. Heavy, irregular irrigations

alternating with prolonged drying cycles tend to reduce both fruit yield and fruit quality, due to increased incidence of blossom-end rot and fruit cracking. Waterlogging and high humidity lead to a greater incidence of pests, diseases, and fruit rot. Excessive wetness can also result in reduced fruit set and fruit yield (Doorenbos and Kassam, 1986).

For drip-irrigated tomato, highest fruit yields can be obtained with irrigation quantities of 0.5-1.0 times pan evaporation depending on soil type, irrigation efficiency, total rainfall and rainfall distribution (Fischer and Nel, 1990; Locascio et al, 1985; Locascio and Smajstrla, 1996; Rhoads and Olson, 1992). Under dry conditions, the yield response to irrigation may be linear up to 1.0 times pan while, during extremely wet years, fruit yield may not be affected by irrigation (Locascio and Smajstrla, 1996; Sammis and Wu, 1986; Vinten et al., 1985).

The use of reduced irrigation rates (deficit irrigation) has a pronounced effect on total fresh fruit weight and yield of extra large fruit, whereas weights of small and medium fruits and total fruit dry weight are affected to a lesser extent (Obreza et al., 1996; Rhoads and Olson, 1992; Smajstrla and Locascio, 1994). The use of deficit irrigation for fresh-market tomato may reduce fruit yields and can increase the incidence of blossom-end rot and fruit cracking while, for processing tomato, it may enhance fruit quality and fruit ripening (Alvino et al., 1988; Obreza et al., 1996; Sanders et al., 1989a).

Irrigation method may affect crop growth and development, fruit yield, and water-use efficiency. With the use of subsurface irrigation, the groundwater table is raised to 0.4 -0.45m below the ground surface and water flux is typically upward (except for periods of heavy rain). All of the fertilizer is commonly applied preplant (Stanley and Clark, 1995).

With high application rates of fertilizer, osmotic stress may reduce initial plant growth while, with low fertilizer rates, nutrient deficiencies during the latter part of the growing season may occur (Scholberg, 1994). High rainfall intensities can result in rise of the water table to within 25-30 cm of the bed surface. This may result in turn, in appreciable "dropout" of N and K from the fertilizer band (Bonczek and McNeal., 1996). It also may increase root decay, and ultimately result in plant wilting. Optimal yields are obtained by maintaining the water table between 45 and 61 cm (Stanley and Clark, 1995).

With drip irrigation, water and fertilizer can be applied in phase with actual crop requirements, resulting in significant reduction in water and nutrient requirements (Hochmuth, 1990). Yields for drip-irrigated crops are similar to those for subirrigated crops, but the use of drip irrigation requires better management skills and is also more expensive (Clark et al., 1989a; Pitts and Clark, 1991; Pitts et al., 1988). The use of drip irrigation leads to root proliferation in the vicinity of the drip emitters and thereby results in the exploitation of a rather small soil volume for water and nutrients. The soil volume beneath the emitters is also highly leached, resulting in reduced concentrations of nutrients. This can be remedied by the use of fertigation.

With the use of drip irrigation seasonal water requirements are on the order of 250-375 mm, compared to 380-1000 mm for overhead, and 1150-1500 mm for subsurface, irrigation (Clark et al, 1989b; Locascio and Smajstrla, 1993; Rhoads, 1990). The use of tensiometers to schedule irrigation allows more efficient water use for drip-irrigated tomato, with seasonal water requirements being further reduced from 400 mm to 160-180 mm. Highest yields are obtained when soil moisture tension is kept around 10-15

kPa (coarse-textured soil) and 20-30 kPa (fine-textured soil), with either wetter or drier soil conditions often resulting in yield reductions (Quaglietta-Chiaranda and Zerbi, 1981; Smajstrla and Locascio, 1996; Vaysse, 1981). The contribution of rainfall to the crop water requirement of mulched tomato depends on rainfall distribution and soil type, with rainfall efficiency typically being only on the order of 0.25 (Rhoads, 1990; Smajstrla and Locascio, 1996). The presence of a shallow water table may contribute up to 16-34% of the water requirement, which can have an appreciable effect on the optimal seasonal irrigation depth for drip-irrigated tomato (Borin, 1990; Vellidis et al., 1988). Water utilization efficiency for harvested yield (E_y) is on the order of 10-12 and 20-30 kg fruit m^{-3} water for furrow and micro irrigation, respectively , but may be as high as 52.5 kg fruit m^{-3} for tensiometer-controlled drip irrigation (Doorenbos and Kassam, 1986, Sammis and Wu, 1986; Smajstrla and Locascio, 1996). Values for total biomass water use efficiency and yield water use efficiency are on the order of 1.3-2.2 and 0.71-1.21 kg dry matter m^{-3}, respectively (Perniola et al., 1994).

Due to the dynamic nature of crop water balance, the effects of water stress on the plant are highly dependent on timing and duration, as well as severity, of the stress (Hsiao, 1981). Pronounced water stress may result in a reduction in plant height, branch number, leaf area, stomatal conductance, leaf size, specific leaf area and total biomass, but moderate water stress during initial vegetative growth reportedly enhances root growth (Doorenbos and Kassam, 1986; Hsiao, 1990; Tan, 1988). Under mild water stress, leaf expansion is most readily reduced, whereas photosynthesis is only reduced (temporarily) due to stomatal closure during periods of high evaporative demand. Under more severe

stress, the photosynthetic capacity of leaves and water use efficiency by the plant are also reduced, with prolonged stress actually resulting in increased leaf aging and senescence (Hsiao, 1990).

Water stress also reduces fruit number and fruit size, which is related to reduced plant size and reduced availability of assimilates, poor pollination, and abortion of young fruits. For branching crops, the number of flower clusters is typically associated with the number of branches and nodes being formed, and a reduction in overall growth will thus result in a smaller number of reproductive sinks and numbers of viable seeds per fruit. Severe water stress during pollination may result in poor fertilization and an appreciable reduction in the number of reproductive sinks, thus causing an irreversible reduction in potential fruit yield. Increasing the availability of water and assimilates after this growth stage may increase fruit size but this may not compensate for the loss of sink sites. Mild water stress during initial growth may enhance earliness due to increased partitioning of assimilates to reproductive growth early in the growing season (Hsiao, 1990).

Plant Nutrition

The fertilizer requirements for high-yielding tomato varieties range from 100-150 kg N ha^{-1}, 65-110 kg P ha^{-1}, and 160-240 kg K ha^{-1} (Doorenbos and Kassam, 1986). In Florida, the recommended N-rate is 196 kg ha^{-1}, and recommended rates for K_2O and P_2O_5 (for soils testing low in P and K) are 150 and 225 kg ha^{-1} for K_2O and P_2O_5, respectively (Maynard and Hochmuth, 1995). Typically, P is banded or broadcast at transplanting. For mulched crops irrigated by subirrigation and overhead irrigation, all N and K is either

applied preplant, broadcast or applied in bands 5 cm deep and 10-15 cm from the transplant row. For drip-irrigated crops, fertilizer can be applied either preplant or by fertigation. With the use of fertigation, 20-25% of N is applied preplant and the remainder is applied at a rate of 1.1-1.7, 1.7-2.8, and 1.1-1.7 kg N ha^{-1} day^{-1} during initial growth, fruit development, and fruit ripening, respectively (Maynard and Hochmuth, 1995).

Commercial applications of fertilizer are often 2-3 times greater than the University of Florida (IFAS) recommendation, while field evaluations of N-fertilization programs don't generally show any positive crop response to N rates in excess of the IFAS-recommended rate (Hochmuth et al., 1989). In other cases, increases in tomato yield up to 300 kg N ha^{-1} have been observed (Everett, 1976; Persaud et al., 1976), but maximum yields can generally be produced with 134-224 kg N ha^{-1} if irrigation and fertilizer management is optimal (Csizinszky and Schuster, 1982; Rhoads et al., 1988; Rhoads et al., 1996; Stanley and Clark, 1995).

Nitrogen Uptake

On a physiological basis, N has the greatest effect on growth rate and plant nutrient uptake rate (Huett and Dettmann, 1988). Although most plants can take up N either as ammonium or nitrate, actual plant growth may be affected by the ratio of these two N-forms in solution (Errebhi and Wilcox, 1990). Nitrate is often a preferential N-source for plant growth, though high carbohydrate levels in the plant favor the uptake of ammonium. The uptake of ammonium is depressed as soil pH falls (Mengel and Kirkby, 1987). Influx of nitrate into the plant occurs both through active and passive uptake. Mass

flow is most important for N uptake when concentrations in the solution are high and when transpiration rates are high, while active uptake becomes relatively more important if concentrations in the soil solution are relatively low (Mengel and Kirkby, 1987). The rate at which nitrogen is absorbed is dependent on its concentration in solution and can be described by the Michaelis-Menten equation

$$I = \frac{I_{max}\,(C - C_{min})}{K_m + (C - C_{min})} \qquad (4)$$

where I = rate of uptake, I_{max} = maximal rate of uptake, K_m = Michaelis-Menten constant, C= concentration of ion at the root surface, and C_{min} = threshold value for ion uptake (Mengel and Kirkby, 1987). The uptake of N by plants appears to be most affected by actual N concentration, rooting volume, root surface area, and I_{max} (Barber and Silverbush, 1984). For tomato, values for I_{max}, K_m, and C_{min} for NO_3 are on the order of 4.5 µmol NO_3 g^{-1} min^{-1}, 41 µmol, and 2-4 µmol, respectively; corresponding values for NH_4^+ are 2.3 µmol NH_4^+ g^{-1} min^{-1}, 8.5 µmol, and 1-2 µmol (Smart and Bloom, 1988).

Daily N-uptake depends on plant size and solution concentration. It increases from 5 mg N $plant^{-1}$ day^{-1} during initial growth to 100-290 mg N $plant^{-1}$ day^{-1} during early fruit development (Bar-Yosef and Sagiv, 1982; Jackson and Bloom, 1990). Total N-uptake was observed to increase linearly up to solution concentrations of 75 ppm NO_3-N, while maximum N-uptake and plant growth occurred at 140-168 ppm N (Bar-Yosef and Sagiv, 1982; Nicola and Basoccu, 1994; Stark et al., 1983). Letey et al. (1982) reported that the ratio of N to water uptake for tomato was fairly constant over a wide range of N

concentrations, but that the overall ratio decreased from 150 mg l^{-1} during initial growth to 70 mg l^{-1} during fruit maturation.

With increasing N-rate, N-partitioning to fruits increases, and total N-accumulation in the fruit and non-reproductive parts increased from 113 to 152 kg N ha^{-1} and from 94 to 239 kg N ha^{-1} as N-rate increased from 0 to 580 kg N ha^{-1} (Stark et al., 1983). At an N-rate of 224 kg N ha^{-1}, total N-uptake by the crop was 167 kg N ha^{-1}, of which 46% was being supplied by soil mineralization. Fertilizer N-recovery by the plants and soil were on the order of 40 and 15%, respectively (Sweeney et al., 1987). The remaining 55% of the applied N was lost due to denitrification, lateral flow, and/or leaching. Stark et al. (1983) reported that potential denitrification rates increased from 0.9 to 4.2 kg N ha^{-1} d^{-1}, as fertilizer rates increased from 120 to 580 kg ha^{-1}.

Leaf tissue N concentrations during initial vegetative growth, early fruit set, and fruit ripening are considered adequate if they are on the order of 3-5%, 2.5-4.0%, and 2.0-3.5%, respectively (Hochmuth et al., 1991). Leaf tissue contents at 70 and 105 days after seeding on the order of 3.1 and 2.4% resulted in maximum yield, with deviations of up to 0.5% resulting in yield reductions of up to 30% (Bar-Yosef and Sagiv, 1982). Yield was observed to be closely related to petiole-sap NO_3-N content (Rhoads et al., 1996). Petiole sap tests can be used as an effective tool to adjust N-fertilizer rates according to actual nutrient concentrations in the plant (Hochmuth, 1990; Huett and Rose, 1988).

Pronounced N-stress may result in reduced growth rates; a reduction in plant height, fruit number, fruit weight, leaf area, leaf size, specific leaf area and total biomass; and an increase in root to shoot ratio (Adams et al., 1973; Nicola and Basoccu,1994).

Typically, the growth response to increased N-rates is quadratic, and increases in biomass and fruit yield are most pronounced under high light conditions, and at N-rates up to 67-134 kg ha^{-1} (Larouche et al., 1989; Masson et al., 1990; Rhoads et al., 1996). Adequate N-supply prior to transplanting may increase initial growth and fruit yield (Melton and Dufault, 1991). Excessively high N-rates during initial growth , on the other hand, may result in excessive vegetative growth, reduced N-uptake efficiency, increased N leaching, and reduced fruit yield (Hochmuth, 1990; Wien and Minotti, 1987). Severe N-stress may retard flower development, while moderate N-stress may increase early fruit yields (Adams et al., 1973; Huett and Dettmann, 1988). Very high N-rates may thus increase total fruit production, whereas early fruit yields, dry matter percentage of the fruit, and percentage of marketable fruits may actually decrease (Kaniszewski et al., 1987; Kooner and Randhawa, 1990). In other cases fruit length, fruit diameter, fruit weight, and soluble solids were reported to increase with increasing N-rates (Huett and Dettmann, 1988; Nassar, 1986).

Nitrogen-Management and Water Quality

Passage of the 1972 Clean Water Act has resulted in increased concerns about possible contributions of agriculture to nonpoint-source pollution of drinking water (Bottcher et al., 1986). As a result, a number of programs have been initiated to monitor ground water quality and to outline alternative production strategies (Best Management Practices or BMP 's) that can minimize groundwater pollution. This development has also resulted in an increased use of simulation models to predict the movement of nitrate in

production systems, and to assess the risk of groundwater contamination (Bottcher et al., 1986).

Crop Modeling

Introduction

There is a extensive body of knowledge on the growth and production of tomato for specific production conditions. However, using this knowledge to predict plant growth for other production systems and environments may not be possible due to the "static" and "reductionistic" approaches often used in agricultural research. During the evaluations of new management strategies and cultivars, experiments therefore need to be repeated for a large number of locations and seasons. This may result in a reduced effectiveness of research, and it also prevents the building of a "dynamic" knowledge base that can be used to predict crop performance for other production systems and seasons (Ritchie, 1991).

Crop modeling allows us to represent our current understanding of biological systems in a condensed and yet comprehensive manner. The use of crop models allows scientists to build on existing knowledge bases and to apply general model structures to a range of specific production systems and environments. In this manner, researchers can be more efficient in their research and also are able to make some inferences on the paths or outcomes of processes over time that would be impractical and/or impossible to evaluate directly (e.g., the effect of global warming on world-wide food production).

Modeling Plant Growth

Although biological processes are more complex than pure physical systems, significant advances in the modeling of agricultural systems have been made by using simplified approaches to model various portions of crop production systems (Ritchie, 1991). To simulate crop yield, both plant growth and development rates need to be considered. Biomass accumulation over time is typically related linearly to the photosynthetically active radiation (PAR) and efficiency of the canopy to intercept PAR (Bennett et al.. 1993; Penning de Vries and Spitters, 1990). Most biochemical processes required for plant growth also require active cell metabolism, with the rate of plant growth thus being temperature dependent (France and Thornley, 1984). The duration of plant growth is determined by both phasic and morphological development rates, which have a pronounced effect on biomass partitioning and the number of plant organs being formed. Process rates vary among cultivars and may also be affected differently by water and nutrient stress (Ritchie, 1991). Based on our understanding of crop growth characteristics, we can model potential growth (growth limited only by radiation and temperature). In a more detailed approach, we can also include the effects of both water and nutrients on plant growth in order to predict attainable yield. Finally, we can include effects of weeds, pests, and disease while predicting actual yields (Goudriaan and van Laar, 1994).

Plant biomass accumulation is affected by photosynthesis, maintenance respiration, and growth respiration. Biomass accumulation over time can be predicted by modeling actual processes for a number of hierarchical levels (the mechanistic approach), or by

assuming a constant dry matter light-use efficiency (the functional approach) as used by Goudriaan and Monteith (1990). In both cases, biomass accumulation depends on light interception and therefore on the prediction of LAI over time (Ritchie, 1991).

The duration of crop development phases can be predicted effectively by using thermal time. This is defined as follows:

$$t_d = \sum_{i=1}^{n} (T_a - T_b) \qquad (5)$$

where T_a is daily mean air temperature and T_b is the base temperature at which development stops, which is around 10 °C for tomato (Wolf et al., 1986). It is assumed that the temperature response is linear and that temperatures will not exceed an upper temperature threshold for extended periods. Jones et al. (1991a) outlined the use of phothermal time to describe the development of soybean, which includes the effect of both day length and temperature on plant development. In this approach a piecewise linear function is defined, which will outline normalized development rates as a function of a wide range of temperatures.

A number of equations have been developed for modeling photosynthesis on a leaf level, using both mechanistical and empirical approaches. An overview of some of these models was presented by Boote and Loomis (1991). To predict canopy photosynthesis, effect of leaf shading on light distribution within the canopy needs to be included in order to predict photosynthesis for crops with LAI greater than unity. Wilkerson et al. (1983) used a simple quadratic form to calculate potential canopy photosynthetic rate of soybean as a function of PAR. By multiplying this potential rate by normalized empirical functions

(to account for the effects of temperature, LAI, N-content of the leaves, and water stress on photosynthesis), actual rates were predicted. A similar approach has been adapted during the development of the CROPGRO model (Hoogenboom et al., 1992).

For most applications, yield predictions are most important and, as a result, partitioning of biomass into various plant parts during crop ontogeny needs to be quantified. The simplest approach is to use a constant harvest index (HI), which is the ratio between total biomass and fruit yield (Ritchie, 1991). Alternatively, it may be assumed that crop yield can be limited by assimilate use (sink-dependent) and/or assimilate production (source-dependent). It is also assumed that assimilates are retranslocated from leaves, stems and roots to sustain reproductive growth (Ritchie, 1991). The combination of these processes results in a dynamic equilibrium, and changes in partitioning coefficients over time can be keyed to phenology of the crop (Wilkerson et al., 1983). Typically, seed growth has priority for assimilate use and the appearance of shell and seed numbers depends on the developmental stage of the crop. The remainder of assimilates can be used for the growth of roots, stems and leaves, based on the development stage and the water and nutrient status of the crop. Leaf area development depends on partitioning of dry matter to the leaves and on environmental factors that affect leaf thickness (Jones and Ritchie, 1992). Root growth and actual root length can be partitioned into different soil zones and Et_a can be computed based on LAI and on the distribution of roots and soil moisture in the soil profile. The ratio of actual to potential evapotranspiration can be used to calculate a stress factor which is used to reduce photosynthesis, plant growth and the partitioning of assimilates to the shoot (Boote et al, 1986).

The development of generic crop models promotes the linking of separate research groups and should facilitate the interchange of information between different regions (Ritchie, 1991). With the establishment of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT), research efforts of a number of modeling groups were linked together, resulting in the development of the Decision Support System for Agrotechnology Transfer (DSSAT) modeling package (Hoogenboom et al., 1992). The generic crop model (CROPGRO) included in this package allows for the simulation of plant growth for a range of field crops and production systems.

Tomato Growth Models

During the past twenty five years a number of models have been developed to simulate the growth and development of tomato. Some of the earlier models used for processing tomato only included simple developmental routines in order to predict the time of harvest (Wilson et al., 1987). Cooper (1972) described dry matter partitioning for greenhouse tomato and worked on calibration of the Thornley partitioning model for greenhouse tomato (Cooper and Thornley, 1976). This model assumed a functional equilibrium between the size and activity of the root (supplying water and nutrients) and the shoot (supplying assimilates for plant growth). It was also used to predict net assimilation rate and relative growth rate (Cooper and Thornley, 1976; Marcelis, 1993).

Acock et al. (1978) developed a model to predict canopy photosynthesis of greenhouse tomato as affected by PAR and CO_2 concentrations. Gent and Enoch (1983) developed a mathematical model that predicted the effect of temperature, light and CO_2

concentrations on vegetative growth and dark respiration of a tomato crop. Kano and van Bavel (1988) outlined a deterministic growth model which included effects of light, temperature, and CO_2 concentrations on plant growth and fruit yield. Jones et al. (1991b) concluded that both source/sink relationships and age structure of state variables needed to be included in order to effectively model the growth of greenhouse tomato. The TOMGRO model developed by this group was designed to respond to rapid changes in environmental conditions inside a greenhouse and, therefore, the model features both a "fast" ($t \leq 1$ h) and a "slow" (daily) loop to simulate plant growth (Jones et al., 1991b). The model uses seven state variables that describe leaf area, node number, leaf number, fruit number, and dry weights of stems, leaves, and fruits as a function of time (Dayan et al., 1993). The change in the number of plant organs within an age class change is calculated based on the initiation rate of the organ, transfer to the next physiological age class, and rate of senescence (leaves) or abortion (fruit) of plant organs. Sink strength of the leaves is calculated by multiplying the potential growth rate in each age class by the number of elements in that class, while stem demand is assumed to be proportional to leaf demand and constant over time. The carbon demand of the fruit depends on development stage and temperature, and is defined based upon the number and specific strength of fruits in each age class (Jones et al., 1991b). The Acock model for canopy photosynthesis is used to calculate the availability of assimilates for plant growth. Assimilate supply is calculated as a function of temperature, light, and CO_2 concentration (Acock et al., 1978; Dayan et al., 1993). Actual organ growth depends on the ratio of carbon supply and demand and, if supply is greater than demand, then the rate of photosynthesis is reduced. Alternately, if

demand is greater than supply, actual growth rates are reduced accordingly (Jones et al., 1991b). The TOMGRO model is one of the few models that predicts fruit set based on the availability of assimilates for newly developed fruits. It appears to be fairly robust under greenhouse settings (Bertin and Gary, 1993).

A number of models have been developed for field-grown tomato. Wolf et al. (1986) developed a model to predict the harvesting date of processing tomato based on the accumulation of heat units. Kropff et al. (1992) used an ecophysiological model to predict yield loss of tomato as affected by weed competition. Bussieres and Dumas (1992) described a conceptual model for the crop management of processing tomato. Wilson et al. (1987) developed a physiological model (TOMSIM) of crop and pest management for processing tomato. This model included effects of water and nutrient stress on plant growth, and was linked to a pest model.

Most crop models are designed to predict dry matter accumulation over time and models are generally calibrated for dry matter production only. However, for the prediction of fresh-market tomato, this approach may not be adequate. The prediction of marketable fruit fresh-weight may be desired if the model will be used for yield predictions (Heuvelink and Marcelis, 1989). Kenig et al. (1993) reported that dry matter content of soybean pods could be predicted based on developmental stage and dry matter content of the canopy. Bussieres (1993) developed a simple model that describes the import of dry matter and water to a tomato fruit as a function of fruit diameter. This model includes the effects of both respiration and transpiration, and allows the prediction of dry matter

content and fruit mass fruit over time (Bussieres, 1994). However, the model needs to be integrated into existing tomato models in order to validate it under field conditions.

Modeling Solute Transfer in Soils

Traditionally, information from field experiments has been used to derive regression models to relate, for example, plant growth to fertilizer and irrigation rates. However, these models do not account for within-season variability in the availability of water and nutrients and cannot be used to predict growth under different conditions. With the development of dynamic simulation models, it has become possible to model the effect of weather variations and of selected soil properties on plant growth and solute movement in the soil. Various simulation models have described nitrogen dynamics in agricultural production systems with varying levels of detail (Godwin and Jones, 1989; Jury and Nielsen, 1989). However, practical application of some of these models is difficult, due to their frequently extensive input data requirements.

Deterministic (mechanistic) models of solute transfer are based upon miscible displacement theory. Use of a mass balance approach combined with flux laws for saturated and/or unsaturated flow allow the prediction of solute concentrations and soil moisture content as a function of time and space. However, spatial variability of water and solute transport parameters in agricultural soils may result in coefficients of variation for apparent solute velocity in field experiments on the order of 40-200%. It thus becomes

difficult to calibrate one-dimensional flow models for one specific average pore volume velocity (Jury and Nielsen, 1989).

Stochastic models describe variables as random functions, which depend in turn on the distribution of values of the soil properties that affect their movement. Stochastic models predict concentration averages and variances, and can be used to calculate the probability that the nitrate concentration will exceed a specific level at a given depth or time (Jury and Nielsen, 1989).

The CERES model simulates plant growth, phenology, water and nitrogen balance, and crop yield. The model was designed to have widespread applicability in diverse environments, using a minimum data set of commonly available field data. The N model is comprised of four subroutines describing N movement, soil N transformations, N uptake, and plant N stress factors. The model uses the "tipping bucket approach" for water percolation, and assumes piston displacement based on a uniform N-distribution within a specific soil layer. The amount of nitrate that is lost from a layer is calculated from the amount of water displaced from that layer (Godwin and Jones, 1989). The water balance used in this model is defined as:

$$S = P + I - EP - ES - R - D \qquad (6)$$

where S = soil moisture, P = precipitation, EP = transpiration, ES = evaporation, R = surface runoff, and D = drainage from the profile. Daily precipitation and irrigation applications are input to the system, while infiltration into the profile is calculated as the difference between precipitation and/or irrigation and runoff. Runoff is calculated using the USDA-Soil Conservation Service curve number approach. Drainage rates are

calculated using an empirical relation based on a fixed saturated volumetric water content (Θ_o) and a fixed upper limit water content (Θ_u), with drainage occuring if Θ_i lies between Θ_o and Θ_u (Johnson and Ritchie, 1989).

Root water absorption is considered to be limited by either soil or root resistance, with the soil-limited water absorption rate being calculated using an empirical equation based on soil hydraulic conductivity, the water potential gradient, root radius, and root length density. The maximum plant-limited flow rate is estimated to be on the order of 0.03 ml cm^{-1} d^{-1} , and evapotranspiration is calculated using a combination of empirical equations for both evaporation and plant transpiration (Jones and Ritchie, 1992).

Fertilizer N is partitioned between nitrate, ammonium, and urea pools according to composition of the fertilizer, assuming uniform fertilizer distribution within the soil. A mineralization routine simulates the decay of both fresh organic matter and the more stable humus pool. Rates are corrected for temperature, moisture condition, and the C/N ratio (Godwin and Jones, 1989). The model calculates both crop demand and soil supply of N separately, and uses the lowest value to determine the actual rate of N uptake by the plant. Demand consists of two components including a deficiency demand, the amount of N required for maintenance purposes, and the amount of N required to produce new plant tissue. Potential N supply is derived empirically from ammonium and nitrate concentrations in solution, and maximum N-uptake from a soil layer is aassumed to be a function of root density, soil moisture, and N concentrations (Godwin and Jones, 1989).

Conclusions

The use of crop models can increase our understanding of biological systems and should facilitate more efficient use of natural resources. Since these models need to be calibrated for specific crops and/or cultivars, detailed growth measures may be required during initial model calibration. In order to apply these models to a wide range of production systems, effects of water and nutrients also need to be included. The initial calibration and validation of these models typically requires a considerable amount of time by a team of multi-disciplinary scientists. However, once developed and tested for their robustness, the models can be used and adapted by researchers throughout the world for a wide range of production systems. The subsequential development of user-friendly interfaces should also result in the application of these models as management tools for both extension workers and commercial producers (Biemond 1989; Hoogenboom et al., 1992).

CHAPTER 3
GENERAL GROWTH CHARACTERISTICS OF FIELD-GROWN TOMATO

Introduction

The original gene center for species within the *esculentum* complex was confined to a coastal strip of 100-300 miles wide in the western part of South America between 2 and 18 °S. However, current commercial production of field-grown tomato is extended to all continents and tomato is grown as far north as Alberta, Canada (55 °N). This increase in production area and in economic importance of the tomato crop has been associated with the development of high-yielding cultivars designed for specific environmental conditions and production systems.

Comprehensive growth studies can increase our understanding of crop response to cultural management practices, and can also be used to evaluate cultivars for their yield potentials. Even though the effects of both water- and nutrient-supply on fruit yield of tomato are well-documented, relatively few studies have included detailed vegetative growth measurements for field-grown tomato.

With an increased interest in the use of crop-growth models to predict harvest date and yield of field-grown tomato, there is also a need for comprehensive growth measurements under well-defined environmental conditions in order to calibrate and validate these models. The development of robust models should also facilitate the

evaluation of new cultivars and production practices under a wide range of environmental conditions. The use of such models should thus allow researchers to use field trials at a number of locations in order to evaluate similar practices for other locations and production seasons. The use of crop modeling thus could both complement field research and assist researchers in becoming more efficient in their research efforts.

During the early eighties an assessment of the plant growth-yield relationships of tomato under field conditions was conducted in Florida (Marlowe et al., 1983). However, this study did not include any information on dry matter partitioning over time nor the mineral content of plant tissue, nor did it include irrigation and fertilization treatments. During the early nineties an opportunity arose to compare predictions from a crop model developed for greenhouse tomato (TOMGRO) with actual growth patterns observed in the field. Field measurements for the calibration of this model were initiated during the spring 1991 production season at Bradenton in west-central Florida, and were continued during the 1992 growing season both at Bradenton and at Immokalee in southwest Florida. Initial calibration results, along with details of the plant growth measurements, were reported by McNeal et al. (1995). I conducted additional growth studies during the 1994, 1995, and 1996 growing seasons. These experiments provided additional information on the effects of water and nutrient supply on plant growth and also included additional locations being: Gainesville (north central Florida), Quincy (north western Florida) and Isabela (northern Puerto Rico). In addition, further studies were conducted during the fall of 1995 at Immokalee and Bradenton, to evaluate the effects of temperature and radiation regimes on plant growth and crop development.

In this chapter, growth characteristics of field-grown tomato are outlined under non-limiting conditions (no obvious water or nutrient stress). Since observed plant growth appeared to be affected by irrigation system, plant growth for subirrigated crops is also compared to that for drip-irrigated crops, and growth analyses are presented separately for both irrigation systems. In Chapter 4, the effects of water stress on photosynthesis, plant growth, and fruit yield are presented. In Chapter 5, effects of N-fertilizer rate on photosynthesis, plant growth, nutrient uptake, and fruit yield are discussed. In Chapter 6, rooting characteristics of tomato in commercial vegetable-beds are presented. In Chapter 6, effects of both water- and nutrient-stress on fruit development and ripening are discussed. Differences in growth characteristics between field-grown crops and greenhouse-grown crops due to cultivar-specific traits and management practices are then discussed in Chapter 7. The growth measurements presented in this chapter were further used to calibrate both the TOMGRO and CROPGRO models (Chapters 8 and 9).

The primary objectives of this chapter are to: (1) outline some of the general growth characteristics of tomato for a number of locations and production seasons; (2) discuss the effects of canopy development over time on radiation interception; and (3) define functional relations for plant growth and biomass accumulation over time.

Materials and Methods

Experiments involving a number of tomato cultivars were initiated during the spring of 1991 at the Gulf Coast Research and Education Center (REC) in Bradenton and were repeated during the growing seasons of 1992 (spring), 1994 (spring), and 1995 (both

spring and fall). Additional experiments were conducted at the Southwest Florida REC in Immokalee during the cropping seasons of 1992 (spring), and 1995 (both spring and fall). Since late-season plant growth during the 1992 growing season was severely affected by diseases, this data set was not included in some of the growth analyses presented below. During the 1995 growing season two additional experiments were conducted at the University of Florida Horticultural Unit in Gainesville (spring) and the North Florida REC in Quincy (spring and fall). Plant growth in Gainesville during the second part of the growing season was affected by water stress due to clogging of the drip emitters, so this study also was not included in some of the growth analysis. During the 1996 spring season the study was repeated along with an irrigation study. The growth study in Puerto Rico was conducted during the winter of 1994 at the Isabela Experimental Substation, with data being obtained from Dr. F.H. Beinroth after being collected by M.A. Vazquez. An overview of planting dates, plant spacing, crop management practices, and experimental treatments is presented in Table 3-1; and an overview of experimental locations within Florida is presented in Fig. 3-1.

The irrigation system used at Bradenton is referred to as a subirrigation (fully enclosed seepage) irrigation system. An overview of this system is presented in Fig. 3-2. With the use of this system the water table is commonly maintained at a soil depth of approximately 45 cm and all of the fertilizer is applied preplant in two bands 15-20 cm to either side of the tomato row. The ample supply of both water and nutrients during initial growth typically results in more vigorous plant growth compared to drip-irrigated crops. However, reported fruit yields for the two irrigation systems were reported to be similar

Table 3-1. Overview of crop management practices for Bradenton (1991,1992,1994,1995), Gainesville (1995, 1996), Immokalee (1995), Puerto Rico (1994), and Quincy (1995).

Location	Cultivar	Planting date (doy)	Plant spacing (m x m)	Plant density (plants ha^{-1})	N Fertilizer rate(s) (kg N ha^{-1})	Fertilization method	Irrigation method
Bradenton-91(S) [y]	Sunny	77	1.37 x 0.75	9,732	230	Banded preplant	Subirrigation
Bradenton-92(S)	Sunny	64	1.52 x 0.61	10,785	180	Banded preplant	Subirrigation
Bradenton-94(S)	Sunny	60	1.52 x 0.61	10,785	180, 258, 336	Banded preplant	Subirrigation
Bradenton-95(S)	Sunny	55	1.52 x 0.61	10,785	0, 100, 200, 300	Banded preplant	Subirrigation
Bradenton-95(F)	Sunny	263	1.52 x 0.61	10,785	200	Banded preplant	Subirrigation
Gainesville-95(S)	Agriset 761	87	1.83 x 0.45	11,960	0, 144, 202, 269, 336	40% Banded preplant 60% Fertigation	Drip irrigation
Gainesville-96(S)	Agriset 761	74	1.83 x 0.45	11,960	0, 144, 202, 269, 336	40% Banded preplant 60% Fertigation	Drip irrigation
Gainesville-96(S)	Agriset 761	88	1.83 x 0.45	11,960	202	40% Banded preplant 60% Fertigation	Drip irrigation Irrigation cutbacks at 14, 35, and 56 days after transplanting.
Immokalee-92(S)	Sunny	37	1.83 x 0.45	11,960	218	20% Banded preplant 80% Fertigation	Drip irrigation
Immokalee-95(S)	Agriset 761	20	1.83 x 0.45	11,960	260	20% Banded preplant 80% Fertigation	Drip irrigation
Immokalee-95(F)	Agriset 761	289	1.83 x 0.45	11,960	218	20% Banded preplant 80% Fertigation	Drip irrigation
Puerto Rico-94(F) [x]	BHN-66	319	1.83 x 0.61	9,042	0, 75, 150, 225	Banded preplant	Drip irrigation
Quincy-95(S)	Agriset 761	87	1.83 x 0.61	9.042	202	Banded preplant	Drip irrigation
Quincy-95(F)	Solarset	199	1.83 x 0.45	11,960	0, 67, 134, 191, 268	Banded preplant	Drip irrigation

y "S" refers to spring crop, and "F" refers to fall crop
x Data were obtained from F.H. Beinroth and collected by M.A. Vazquez

as long as both systems are managed properly (Clark et al., 1989a; Pitts and Clark, 1991). Although water use is typically lower with drip irrigation than with subirrigation (Locascio and Smajstrla, 1993), parts of the bed (especially with coarse-textured soils) may remain dry. Nutrients are also more prone to leaching or may accumulate in dry portions of the bed, unavailable for plant uptake. As a result, drip irrigation requires better management skills, since both water and nutrients must be applied in phase with actual crop requirements in order to prevent either water-stress or excessive leaching of nutrients. Typically only 20-40% of fertilizer is applied preplant (Table 3-1), with the remainder being supplied with the irrigation water. Ideally, water supply is also based on crop evapotranspiration and/or based on the readings from tensiometers placed in the production beds. It was thus hypothesized that, due to potential differences in water and nutrient management, actual plant growth may be different for these two irrigation

Fig. 3-1 Experimental locations within Florida.

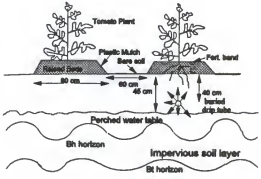


Fig. 3-2 Overview of fully enclosed seepage irrigation system, Bradenton, Fla.

systems. Therefore, the results of the growth studies are presented separately for subirrigated crops and drip-irrigated crops.

Weather data were collected daily from either on-site stations (Bradenton, Immokalee, and Quincy) or from a nearby weather station (Gainesville and Isabela). Averaged values for these locations are presented in Appendix B, Tables 1 through 3. Reported radiation values were plotted vs potential radiation values generated by a FORTRAN77 program assuming an atmospheric transmission coefficient of 0.775 (Scholberg, 1994). Radiation values for the data set should, at least on a number of (perfectly clear) days, be equal to potential radiation. If this did not occur, the radiation data were either multiplied uniformly by an appropriate constant to effect such behavior, or data were replaced by radiation data from other recording stations nearby.

The soils at Bradenton and Immokalee were mapped as Eaugallie fine sand (sandy, siliceous, hyperthermic, Alfic Haplaquads) and Myakka fine sand (sandy, siliceous, hyperthermic, Aeric Haplaquods). The soils at Gainesville, Isabela, and Quincy were a Millhopper fine sand (loamy, siliceous, hyperthermic, Grossarenic Paleudults); a Coto clay (clayey, kaolinitic, isohyperthermic, Inceptic Hapludoxes), and a Orangeburg loamy sand (fine-loamy, siliceous, hyperthermic, Typic Paleudults), respectively. Soil characteristics for these soils are presented in Appendix B, Tables 4 through 8.

At Bradenton, representative plants from the guard rows of subirrigated trials were sampled approximately biweekly during the 1991 and 1992 growing seasons. A total of four plants were sampled destructively on each sampling date. After labeling selected plants, plant height and canopy width were recorded and, subsequently, support

strings were cut and plants were severed at ground height. Main-stem nodes and numbers of branches, leaves, and flower clusters were counted before measuring total fresh weights of leaves (leaf blades and petioles), stems, and fruits. Subsequently a representative leaf subsample (approx 100 g) was taken, leaf blades were separated from petioles, and this subsample was run through a leaf-area meter in order to calculate the leaf area index (LAI) of the plant. Subsamples of petioles, leaf blades, stems, and fruits were dried at 65° C prior to dry weight determinations, followed by grinding and elemental analysis. Considerable effort was expended on the below-ground portion of the plant on each sampling date as well during the 1991, 1992, and 1995 growing seasons. Roots were excavated up a soil depth of 30 cm either by using a spade, or by washing away all of the soil in prescribed sections of the production bed. In this chapter, only root biomass will be presented. A more detailed description of the root sampling methodology employed, along with a discussion of root-length and nutrient distribution within the production beds, will be presented in Chapter 6.

During the 1994 and 1995 growing seasons for Bradenton, representative plants were obtained from actual research plots and two or three plants, respectively, were sampled per fertilizer treatment during 1994 and 1995. Atypical plants, plants near gaps, or plants planted later to fill gaps were rejected during sampling and only healthy-looking plants were sampled, unless less robust plants appeared representative of a specific fertilization or irrigation treatment. Sampling procedures for drip-irrigated crops were the same as those outlined above, except that the number of plants sampled was either two (Gainesville 1996, N-fertilizer study); three (Gainesville 1996, irrigation study;

Immokalee 1995; and Quincy 1995); or four (Immokalee 1992 and Puerto Rico 1994). Sampling intervals varied from two weeks (Immokalee 1992 and 1995; Gaineville 1995; and Puerto Rico 1994) or three weeks (Gainesville 1996; Quincy fall 1995) to approximately four weeks (Quincy spring 1995). The fall crops at Bradenton and Immokalee were sampled at two- and four-week intervals, respectively. However, during these studies, sampling only started 9 weeks after transplanting. This chapter only includes N-rate treatments for which the actual rate should provide an adequate supply of N for optimal plant growth, which generally corresponds to an N-rate of 180 to 240 kg ha^{-1}. During growth analysis a base temperature for tomato of 10 °C was used. This value was based on reports by Wolf et al. (1986) and Jones et al. (1989b). However, reported values for the base temperatures for tomato may range from 6 to 13 °C, depending on the growth stage and the method used for calculating heat units (Lipari et al., 1988). During the approach presented here, thermal time was calculated by subtracting ten from the average daily minimum and maximum air temperatures. If the resulted values were negative, thermal time increments for that day were set to zero. Radiation interception was calculated by using the following equation:

$$RAD_{abs} = (1 - \exp^{-k \cdot LAI}) \qquad (1)$$

where k= light extinction coefficient for which a value of 0.60 was assumed (Challa and Heuvelink, 1993). Radiation interception values where then multiplied with daily solar radiation values. Subsequently, dry weight accumulation was plotted versus either thermal time or cumulative intercepted daily radiation (Bennett et al., 1993).

Results and Discussion

The number of main-stem nodes formed typically ranged from about 18 to 22 (Tables 3-2 through 3-4). Values reported during the second part of the 1992 growing season in Bradenton appeared to be high (Table 3-2), with it being possible that continued node growth of lateral branches was inadvertently included in the main-stem node number for this study. Typically, main-stem node formation ceases after the formation of a terminal fruit cluster, and node formation is continued only via lateral shoots (Fig. 3-3). An apparent reduction in node number towards the end of the growing season (Immokalee 1992 and 1995) may be attributed to the senescence of lower leaves so that the associated nodes were no longer detected.

The overall rate of development for tomato as affected by irrigation system was compared by plotting node number formed after transplanting vs thermal time (Fig. 3-4a and 3-4b). The slopes for the fitted lines were 0.029 and 0.030 nodes °Cd $^{-1}$ for drip irrigation and subirrigation, respectively. Assuming a base temperature of 10 °C and a maximum node development rate at 28 °C, these values translate into a node-development rate of 0.52 and 0.54 nodes d $^{-1}$. This compares favorably with the value of 0.5 nodes d $^{-1}$ reported by Jones et al. (1989b). Based on this analysis, rates of

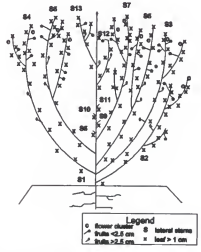


Fig. 3-3. Branching characteristics for drip-irrigated tomato (Gainesville 1993).

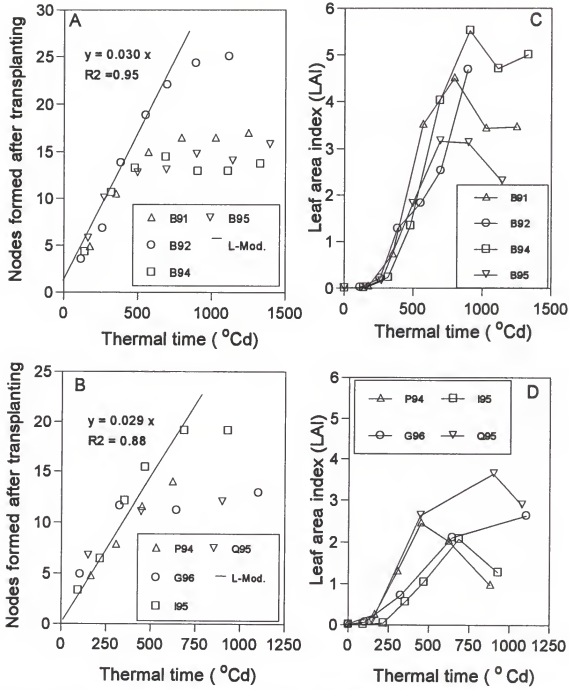


Fig. 3-4. Node number formed after transplanting for a) subirrigated tomato crops at Bradenton for the 1991(B91), 1992 (B92), 1994 (B94), and 1995 (B95) growing seasons; and b) drip-irrigated crops at Puerto Rico for 1994 (P94), at Gainesville for 1996 (G96), at Immokalee for 1995 (I95), and at Quincy for 1995 (Q95). Node numbers were fitted by using linear regression (L-mod.), expressing node number (y) as a function of thermal time (x); c) Leaf area index for subirrigated tomato crops; and d)Leaf area index for drip-irrigated crops.

Table 3-2. Summarized growth measurements for subirrigated tomato crops, Bradenton spring seasons of 1991, 1992, 1994 and 1995.

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
Bradenton -1991 [1]							
15	7.9 ± 0.5	0.04 ± 0.00	0.3 ± 0.0	0.5 ± 0.1	1.3 ± 0.1		2.1 ± 0.2
29	13.5 ± 0.2	0.73 ± 0.05	2.2 ± 0.3	7.0 ± 1.4	25.1 ± 1.8		4.3 ± 3.4
44	18.0 ± 1.9	3.51 ± 0.23	11.0 ± 1.0	100 ± 5.6	98.3 ± 5.1	18.7 ± 2.4	228 ± 9.1
58	19.5 ± 1.7	4.50 ± 0.40	20.0 ± 4.5	179 ± 8.9	149 ± 7.6	84.3 ± 7.6	432 ± 21.3
73	19.5 ± 2.7	3.45 ± 0.67	15.4 ± 1.1	202 ± 26.3	112 ± 15.7	300 ± 122	629 ± 46.5
87	20.0	3.48 ± 0.22	19.3 ± 0.8	268 ± 27.7	127 ± 3.6	362 ± 33.2	776 ± 51.0
Bradenton -1992 [1]							
13	8.0 ± 0.0	0.02 ± 0.00		0.4	0.7		1.3 ± 0.1
30	11.3 ± 0.5	0.21 ± 0.01		6.7 ± 0.1	8.7 ± 0.4		15.4 ± 0.4
42	18.3 ± 1.6	1.28 ± 0.07	7.1 ± 0.2	31.5 ± 0.8	33.1 ± 0.6	2.5 ± 0.8	79.3 ± 1.8
55	23.3 ± 0.5	1.82 ± 0.10	9.7 ± 0.7	68.6 ± 2.1	64.3 ± 1.4	46.9 ± 1.9	190 ± 3.7
70	26.5 ± 1.0	2.53 ± 0.10	11.3 ± 1.0	94.1 ± 2.1	80.2 ± 2.5	196 ± 9.4	382 ± 8.0
84	28.8 ± 2.0	4.69 ± 0.26	12.6 ± 1.0	163 ± 7.5	136 ± 4.8	452 ± 10.6	763 ± 22.9
98	29.5 ± 0.9			169 ± 7.2	138 ± 10.9	596 ± 54.2	903 ± 131
Bradenton -1994 [2]							
0	3.1 ± 0.1	0.002 ± 0.0		0.06 ± 0.00	0.09 ± 0.00		0.15 ± 0.01
16	7.3 ± 0.5	0.009 ± 0.0	0.07 ± 0.01	0.19 ± 0.02	0.35 ± 0.03		0.61 ± 0.05
30	14.0 ± 0.0	0.22 ± 0.0	1.2 ± 0.02	5.2 ± 0.24	8.2 ± 0.13		14.6 ± 0.4
44	16.5 ± 1.5	1.17 ± 0.1	3.9 ± 0.2	40.7 ± 1.8	40.5 ± 3.3		92.3 ± 6.4
58	18.5 ± 0.5	3.18 ± 0.38	5.7 ± 1.5	99.0 ± 17.9	81.5 ± 14.2	70.6 ± 2.1	257 ± 35.6
72	14.5 ± 0.5	6.00 ± 0.52	9.8 ± 0.2	211 ± 8.0	172 ± 3.8	372 ± 45.0	764 ± 49.0
86	16.5 ± 0.5	4.19 ± 0.78	6.7 ± 0.3	137 ± 25.6	120 ± 17.6	507 ± 19.8	771 ± 63.2
100	17.0 ± 1.0	5.26 ± 0.41	10.4 ± 1.1	211 ± 7.6	158 ± 14.8	763 ± 127	1142 ± 150
Bradenton -1995 [3]							
0	4.3 ± 0.2	0.003 ± 0.0	0.07 ± 0.00	0.06 ± 0.00	0.09 ± 0.0		0.21 ± 0.01
14	10.7 ± 0.3	0.020 ± 0.0	0.11 ± 0.02	0.26 ± 0.02	0.70 ± 0.1		1.11 ± 0.10
26	15.0 ± 0.0	0.15 ± 0.01		3.1 ± 0.1	4.8 ± 0.6		8.0 ± 0.7
46	17.7 ± 0.6	1.83 ± 0.34		55.2 ± 6.4	48.7 ± 4.5	4.3 ± 1.8	108 ± 9.8
60	18.0 ± 0.5	3.19 ± 0.35		102 ± 4.8	79.3 ± 4.5	100 ± 3.1	288 ± 10.9
74	19.7 ± 1.9	3.15 ± 0.38		118 ± 15.3	86.7 ± 9.2	267 ± 26.0	486 ± 17.9
88	19.0 ± 1.5	2.28 ± 0.20		138 ± 7.9	82.3 ± 6.0	423 ± 25.5	679 ± 23.0
102	20.7 ± 1.0	0.57 ± 0.29		112 ± 25.3	23.9 ± 12.4	342 ± 27.5	553 ± 60.8

[1] Values are averages of 4 replicates

[2] Values are averages of 2 replicates for the 258 kg N ha^{-1} treatment

[3] Values are averages of 3 replicates for the 200 kg N ha^{-1} treatment

Table 3-3. Summarized growth measurements for drip-irrigated tomato crops, Gainesville 1995, Immokalee 1992 and 1995, and Quincy 1995.

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
Gainesville-1995 [1]							
0	4.9 ± 0.2	0.003 ± 0.0	0.05 ± 0.0	0.08 ± 0.01	0.12 ± 0.01		0.25 ± 0.02
21	12.0 ± 0.6	0.08 ± 0.01	0.38 ± 0.1	1.6 ± 0.1	2.7 ± 0.1		4.6 ± 0.1
35	15.3 ± 0.9	0.63 ± 0.04		20.1 ± 0.9	22.5 ± 0.9	0.2 ± 0.1	43.3 ± 2.0
49	17.7 ± 0.3	1.25 ± 0.23		57.9 ±10.2	41.8 ± 7.1	39.3 ± 4.8	138 ± 22.1
63	19.0 ± 0.8	1.54 ± 0.10		78.6 ± 4.7	59.9 ± 6.7	116 ± 11.0	254 ± 22.6
78	16.3 ± 1.3	0.97 ± 0.12		73.8 ± 4.2	41.6 ± 6.0	126 ± 3.7	242 ± 9.5
94	18.0 ± 0.6	0.65 ± 0.27		87.0 ± 7.7	27.7 ± 10.9	148 ± 13.2	280 ± 23.6
Gainesville-1996 [2]							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
35	13.0 ± 0.0	0.14 ± 0.02		2.8 ± 0.23	4.7 ± 0.6		7.6 ± 1.7
56	19.0 ± 0.8	1.84 ± 0.29		85.4 ± 10.8	65.0 ± 5.4	12.3 ± 0.4	162 ±16.5
77	19.0 ± 0.8	2.22 ± 0.04		125 ± 28.8	83.1 ± 10.3	217 ± 5.4	426 ±24.3
91	20.0 ± 0.0	2.36 ± 0.07		134 ± 34.7	92.7 ± 9.9	253 ± 11.2	479 ±18.7
Immokalee-1992 [3]							
21	9.5± 0.3	0.03 ± 0.00	0.16 ± 0.01		0.43 ± 0.07	0.77 ± 0.07	1.36 ± 0.23
39	13.3± 1.2	0.23 ± 0.03	1.74 ± 0.33	6.4 ± 0.9	8.08 ± 1.1		16.2 ± 2.28
54	13.3± 0.8	0.83 ± 0.02		25.8 ± 1.3	32.6 ± 1.4	10.8 ± 4.3	69.3 ± 5.30
68	12.8± 0.5	1.30 ± 0.10	8.5 ± 0.72	54.5 ± 2.8	53.6 ± 6.0	61.6 ± 5.6	178 ± 12.0
82	10.5± 0.9	0.63 ± 0.12		44.2 ± 4.8	37.7 ± 4.3	107 ± 7.6	189 ± 15.5
Immokalee-1995 [1]							
0	3.9 ± 0.1	0.002 ± 0.0	0.03 ± 0.0	0.06 ±0.02	0.05 ± 0.0		0.14 ± 0.00
21	7.2 ± 0.3	0.01 ± 0.00	0.04 ± 0.0	0.09 ± 0.1	0.3 ± 0.0		0.40 ± 0.02
34	10.3 ± 0.3	0.04 ± 0.00	0.83 ± 0.1	1.5 ± 0.1	2.6 ± 0.0		5.2 ± 0.15
48	16.0 ± 1.0	0.43 ± 0.06	3.1 ± 0.4	9.8 ± 1.5	14.0 ± 1.8	0.5 ± 0.1	27.4 ± 3.2
62	19.3 ± 2.9	0.76 ± 0.19	7.7 ± 1.4	25.1 ± 6.5	24.1 ± 4.5	12.8 ± 4.1	70.3 ± 16.7
80	22.5 ± 0.3	1.41 ± 0.31	3.9 ± 1.0	49.8 ± 8.1	43.1 ± 8.2	72.0 ± 13.3	176 ± 25.2
94	19.0 ± 2.1	1.54 ± 0.54		67.2 ±21.4	49.5 ± 18.0	185 ± 34.4	317 ± 46.4
Quincy -1995 [1]							
20	11.7 ± 0.3	0.07 ± 0.01	0.5 ± 0.03	1.8 ± 0.1	3.8 ± 0.2		6.2 ± 0.3
47	16.7 ± 1.3	2.41 ± 0.44	2.3 ± 0.43	86.4 ± 8.7	79.8 ± 9.0	21.4 ± 2.3	193 ± 16.2
76	17.0 ± 0.0	2.99 ± 0.67		148 ± 30.7	114 ± 24.0	297 ± 67.9	667 ± 125
90	24.7 ± 2.6	2.89 ± 0.12		171 ± 7.2	103 ± 11.2	456 ± 28.3	729 ± 32.6

[1] Values are averages of 3 replicates for the 202 kg N ha^{-1} treatment

[2] Values are averages of 2 replicates for the 202 kg N ha^{-1} treatment

[3] Values are averages of 4 replicates for the 225 kg N ha^{-1} treatment

Table 3-4. Summarized growth measurements for fall tomato crops, Bradenton 1995 (subirrigated), Immokalee 1995 (drip-irrigated), Quincy 1995 (drip-irrigated), and Isabela, Puerto Rico 1995 (drip-irrigated).

			Dry weight per plant (g)				
DAP	Node No.	LAI	Roots	Stems	Blades	Fruit	Total
Bradenton-1995 [1]							
62	17.5 ± 0.5	4.26 ± 0.13		141 ± 1.0	111 ± 11.8	72.5 ± 15.0	325 ± 26.4
76	22.3 ± 0.9	4.43 ± 0.50		164 ± 16.8	127 ± 17.6	206 ± 24.6	501 ± 58.2
90	21.5 ± 2.5	5.25 ± 0.27		163 ± 7.4	142 ± 12.7	406 ± 9.1	721 ± 8.4
Immokalee -1995 [1]							
64	21.0 ± 3.0	4.24 ± 0.13		148 ± 4.8	94.2 ± 12.9	55.1 ± 7.0	298 ± 11.0
99	19.5 ± 1.5	2.90 ± 0.44		144 ± 13.6	91.1 ± 11.5	328 ± 24.9	563 ± 50.3
Puerto Rico -1994 [2]							
15		0.02 ± 0.0	0.08 ± 0.0	0.16 ± 0.0	0.75 ± 0.1		1.00 ± 0.10
29		0.24 ± 0.05	1.4 ± 0.2	2.2 ± 0.5	10.4 ± 2.3		13.9 ± 2.9
43		1.30 ± 0.09	3.3 ± 0.4	17.7 ± 1.5	52.2 ± 6.1	0.9 ± 0.3	73.9 ± 7.9
57		2.45 ± 0.19	5.3 ± 0.4	33.5 ± 0.8	85.3 ± 4.8	57.7 ± 5.2	182 ± 10.5
76		2.02 ± 0.17	5.5 ± 0.4	43.0 ± 2.6	106 ± 5.5	289 ± 45.6	443 ± 53.2
84		0.97 ± 0.09	4.5 ± 0.8	36.9 ± 3.8	76.8 ± 6.5	293 ± 38.2	411 ± 47.7
Quincy -1995 [3]							
0	6.3 ± 0.2	0.004 ± 0.0	0.14 ± 0.01	0.3 ± 0.01	0.2 ± 0.01		0.66 ± 0.03
23	14.3 ± 0.3	0.17 ± 0.03	0.70 ± 0.1	5.5 ± 0.9	7.6 ± 1.4		13.8 ± 2.3
43	17.3 ± 0.3	1.25 ± 0.12		54.6 ± 4.3	47.0 ± 5.0	1.0 ± 1.0	106 ± 10.8
63	17.7 ± 0.7	2.94 ± 0.26		137 ± 15.3	81.6 ± 5.7	44.7 ± 4.6	271 ± 14.7
84	18.7 ± 1.2	1.99 ± 0.30		124 ± 11.5	65.1 ± 6.7	272 ± 14.6	506 ± 37.8

[1] Values are averages of 3 replicates for the 180 kg N ha^{-1} treatment
[2] Values are averages of 4 replicates for the 225 kg N ha^{-1} treatment
[3] Values are averages of 3 replicates for the 191 kg N ha^{-1} treatment

development appear to be similar for both irrigation systems and main-stem node formation typically "tailed off" after the accumulation of 500 to 600 °Cd.

Maximum values of the leaf area index (LAI) for subirrigated crops ranged from 3.19 to 6.00 for the 1995 and 1994 growing seasons (Table 3-2). Overall LAI values for drip-irrigated crops appeared to be lower than those for subirrigated crops (Tables 3-3 and

3-4), with values ranging from 1.3 (Immokalee 1992) to 4.2 (Immokalee fall 1995). Peak LAI values below 2.0 were attributed to poor crop growth due to water and/or nutrient stress (Gainesville 1995, Immokalee 1995) and/or to rapid canopy senescense due to incidence of plant pests and/or diseases (Immokalee 1992). Reported LAI values for subirrigated field crops and drip-irrigated greenhouse crops were on the order of 5.5- 6.5 and 7-8, respectively (Marlowe et al., 1983; Jones et al., 1989b).

Plotting LAI values for subirrigated crops vs real time yielded distinct curves, with canopy build-up appearing to be more rapid for later planting dates (Scholberg, 1994). The use of thermal time resulted in much more similar canopy-development curves (Fig. 3-4c). The maximum leaf area for subirrigated crops appeared to occur after the accumulation of 800 to 900 °Cd and was invariably followed by a decrease in LAI. The incidence of foliar diseases during the second part of the 1995 growing season resulted in a more rapid onset of canopy senescence. Differences in canopy development between drip-irrigated crops may be related to crop management, soil type, and planting time (Fig. 3-4d). The slow initial canopy development at Immokalee may have been caused by cold injury during initial growth. It is of interest to note that crops grown on finer-textured soils (Puerto Rico and Quincy) showed faster initial canopy development than for crops grown on coarse-textured soils (Gainesville and Immokalee). This may be related to differences in either water and/or nutrient retention.

Calculated values for light interception by tomato crops were lower with drip irrigation than with subsurface irrigation, with respective values of 0.8-0.9 and 0.6-0.8 (Fig. 3-5). Bennett et al. (1993) reported, for peanuts, that approximately 90% and 95%

of the photosynthetically active radiation (PAR) was intercepted at LAI values of 2.3 and 4, respectively. Corresponding values for tomato were 3.6 and 4.6, respectively. Jones (1979) reported that a reduction in canopy area of subirrigated tomato, which typically has LAI values of 5 to 6, by 10-20% did not significantly affect fruit yield.

It thus may be concluded that maximum fruit yields can be attained at LAI values of 3.6 to 4.6. Lower LAI values may reduce light interception and may also increase yield losses due to sunburn. Higher LAI values may be indicative of excessive vegetative growth, which may delay the onset of fruit production and also may reduce the effectiveness of foliar applications of pesticides. It is of interest to note that higher LAI values for subirrigated crops also coincide with a smaller interrow spacing and a greater distance between plants. It could be hypothesized that this plant arrangement may have

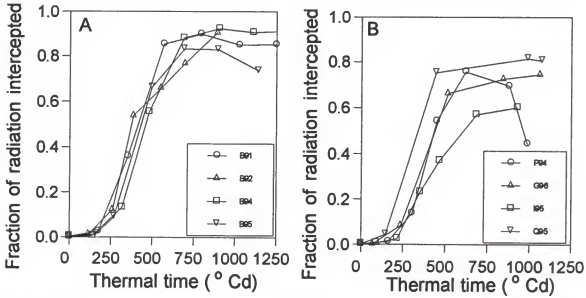


Fig. 3-5. Fraction of radiation intercepted for a) subirrigated crops at Bradenton for the 1991 (B91), 1992 (B92), 1994 (B94), and 1995 (B95) growing seasons; and b) drip-irrigated crops at Puerto Rico for 1994 (P94), at Gainesville for 1996, at Immokalee for 1995 (I95), and at Quincy for 1995 (Q95). Light interception for observed LAI values was calculated using equation 1, and assuming a value of 0.60 for k.

resulted in increased light interception. Tomato plants typically are capable of adapting their canopy architecture according to specific plant arrangements. However, staking and tying of the crop typically confines the canopy width to 0.8-1.2 m, depending on plant vigor and management practices. As a result, canopy closure for field-grown tomato within the row is attained within 4 to 6 weeks for intrarow spacings of 45 and 60 cm, respectively. Canopy closure between rows, on the other hand, typically does not occur. Based on a maximum canopy width of 1.0 m, the percentage ground area covered by the crop would be on the order of 83, 67, 55% for row spacings of 1.2, 1.5, and 1.8 m, respectively. Increasing intrarow spacings (Bradenton) may thus have delayed interplant competition for light and, along with narrower interrow spacing, this may have resulted in increased light interception and yield increases on the order of 15-25%. This appears to be in agreement with observations in the field, where a row spacing of 1.2 m for a drip-irrigated crop resulted in marketable fruit yields on the order of 110 t ha^{-1} (Hochmuth, 1996) compared to fruit yields of 60-90 t ha^{-1} (Locascio and Smajstrla, 1996; Rhoads et al., 1996) for crops with a row spacing of 1.8 m. It appears that current practices and recommendations for plant spacings may be based on past fertilization and irrigation practices (G.J. Hochmuth, personal communication). With the use of drip irrigation and N-fertilization rates in line with current IFAS (Institute of Food and Agricultural Sciences, at the University of Florida) fertilization recommendations, vegetative growth may be less vigorous. This should allow reduced row spacings.

The linear relationship between log-transformed leaf area measurements and node number (Fig. 3-6) appeared to apply to both irrigation systems, although slopes and

intercepts were slightly different. This general relation appeared to also be valid for greenhouse tomato (Scholberg, 1994). Plotting log-transformed LAI values vs real time resulted in a logistic curve instead (data not shown). The linear relation defined in Fig. 3-6a appeared to be useful for finding intermediate values for the LAI vs the node-number look-up function used in the CROPGRO growth model (Chapter 9).

During initial growth, weights of leaf blades were typically higher than stem weights (including leaf petioles) while, towards the end of the growing season, the reverse was true (Tables 3-2 through 3-4). Stem weights appeared to be exceptionally low for the Puerto Rico data set (Table 3-4). It is possible that petiole weight was not included with the stem weight in this case. By the end of the growing season, dry matter accumulation in roots, stems, and leaf blades accounted for roughly 3%, 23%, and 17% of the total biomass, respectively.

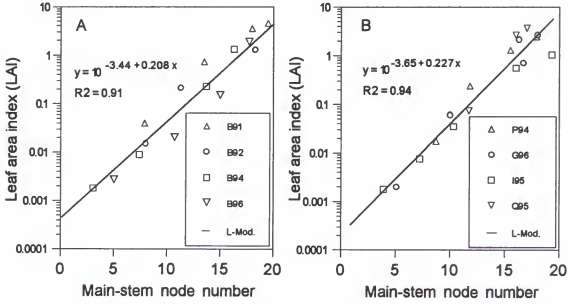


Fig. 3-6. Leaf area index (LAI) vs number of main-stem nodes for a) subirrigated crops; and b) drip-irrigated crops. The LAI values were fitted using linear regression (L-Mod.), expressing LAI (y) as a function of node number (x).

Overall biomass production was on the order of 6 and 9 t ha^{-1} for drip-irrigated and subirrigated crops, respectively. Harvest indices (HI) ranged from 0.53 to 0.71. Respective HI values for drip-irrigated and subirrigated crops were 0.60 and 0.53, respectively. However, it was observed that higher HI values were often associated with better crop management, and that high-yielding crops typically had HI values on the order of 0.65 regardless of the irrigation system. As stated before, drip irrigation requires better management skills and it appeared that, in a number of cases, the low yields for drip-irrigated trials were associated with management problems. However, under optimal management conditions, marketable fruit yield and total dry weight for drip-irrigated crops at research facilities in Florida should be on the order of 60-90 t ha^{-1} and 6-9 t ha^{-1}, respectively .

In Figs. 3-7a and 3-7b biomass accumulation is presented as a function of thermal time. The approach presented here is similar to the one used by Goudriaan and van Laar (1994). However, in order to combine the results of different experiments, thermal time is used instead of real time. During the initial growth phase, biomass accumulation by tomato plants is limited due to low canopy interception of PAR (Hsiao, 1990). This phase is followed by a linear growth phase, which starts at 330 and 300 ° Cd for subirrigated and drip-irrigated crops, respectively (Fig. 3-7a and 3-7b). These values correspond to a LAI of approximately unity (Fig. 3-4c and 3-4d). The slopes of the lines are the potential growth rate expressed in thermal time (g dw m^{-2} $°Cd^{-1}$). Respective values for potential growth rates were on the order of 1.07 and 0.80 g dw m^{-2} $°Cd^{-1}$ for subirrigated and drip-irrigated crops.

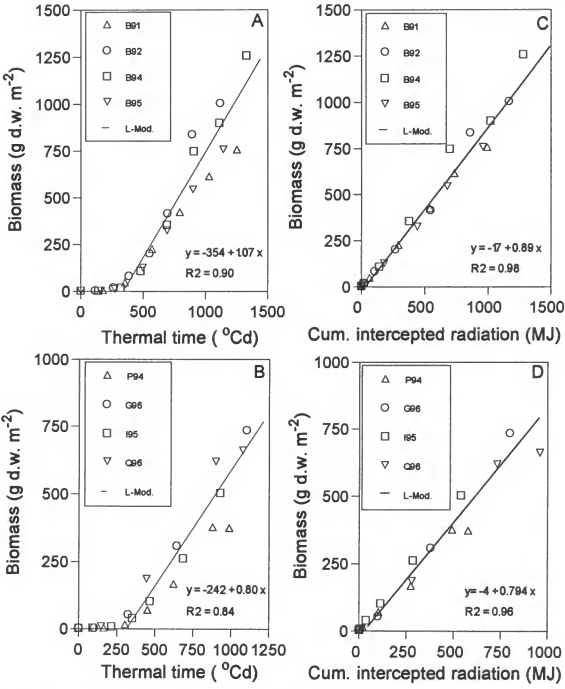


Fig 3-7. Biomass production vs thermal time for a) subirrigated crops at Bradenton for the 1991 (B91), 1992 (B92), 1994 (B94), and 1995 (B95) growing seasons; b) drip-irrigated crops at Puerto Rico for 1994 (P94), at Gainesville for 1996 (G96), at Immokalee for 1995 (I95), and at Quincy for 1995 (Q95); Biomass production vs cumulative intercepted radiation for c) subirrigated crops; and d) dripirrigated crops. Biomass weights were fitted using linear regression (L-Mod.), expressing biomass weight (y) as a function of either thermal time (a and b) or cumulative intercepted radiation (c and d).

In Figs. 3-7c and 3-7d, biomass accumulation is shown to also be linearly related to cumulative intercepted radiation. The approach used here is slightly different from that proposed by Bennett et al. (1993). In their approach, radiation use efficiency (g biomass produced per MJ radiation intercepted) was calculated using light interception and seed weights were converted to "vegetative weight equivalents". In the approach used here, radiation use efficiency (RUE) is only calculated during the linear growth phase and, since the seed fraction of tomato is relatively small (<4% of the total biomass), no further corrections were used. Values of RUE for tomato were on the order of 0.89 and 0.79 g MJ^{-1} for subirrigated and drip-irrigated crops, respectively. This compares favorably to the value of 0.76 g MJ^{-1} reported for peanut (Bennett et al., 1993). Lower RUE values for drip-irrigated crops can be attributed to lower LAI values (Figs. 3-4c and 3-4d), resulting in less-complete interception of solar radiation (Fig. 3-5). This seems to provide further support for the hypothesis that crop yields of drip-irrigated tomato could be increased by reducing row spacing and increasing plant densities.

In similar fashion, fruit dry weights are shown to be a function of thermal time (Figs. 3-8a and 3-8b). Fruit growth rates were 0.90 and 0.66 g dw m^{-2} °Cd $^{-1}$ for subirrigation and drip irrigation, respectively. Lower fruit growth rates with drip irrigation are probably related to lower RUE and lower harvest index values. Based on the results shown in Figs. 3-8c and 3-8d, it may be concluded that the RUE for fruit dry matter is 0.67 and 0.55 g MJ^{-1} for subirrigated and drip-irrigated crops, respectively. Observed differences in RUE values at Immokalee for both fruit and biomass appear to be related to cold temperatures during initial growth (resulting in a later onset of the linear growth

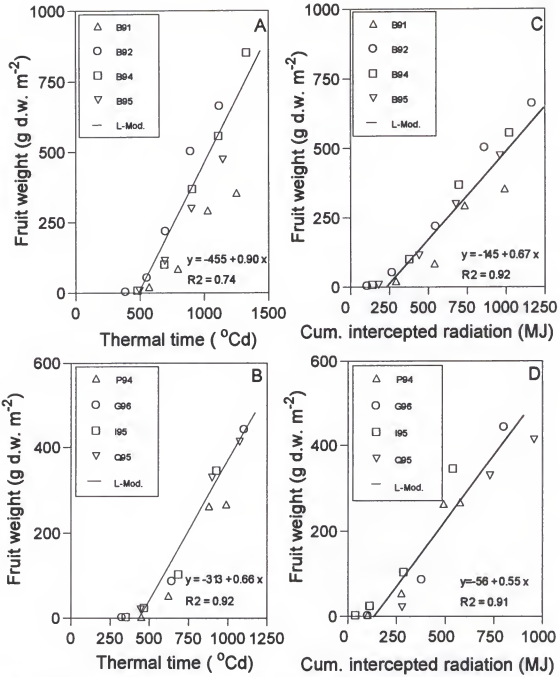


Fig. 3-8. Fruit dry weight vs thermal time for a) subirrigated crops at Bradenton for the 1991 (B91), 1992 (B92), 1994 (B94), and 1995 (B95) growing seasons; b) drip-irrigated crops at Puerto Rico for 1994 (P94), at Gainesville for 1996 (G96), at Immokalee for 1995 (I95), and at Quincy for 1995 (Q95); Fruit dry weight vs cumulative intercepted radiation for c) subirrigated crops; and d) drip-irrigated crops. Fruit weights were fitted using linear regression (L-Mod.), expressing fruit dry weight (y) as a function of either thermal time (a and b) or cumulative intercepted radiation (c and d).

phase) or to N-stress during the second part of the season (resulting in a decrease in RUE). Effects of N-stress on RUE will be presented in Chapter 5.

Conclusions

Based on the results presented here it may be concluded that LAI values for a mature tomato crop ranged from 3.5 to 5.5, and from 2.0 to 4.0 for subirrigated and drip-irrigated crops, respectively. Maximum light interception was 0.9 and 0.8 for subirrigated and drip-irrigated crops, respectively. Based on the analysis presented here its is concluded that maximum fruit yields can be obtained with LAI values around 4 to 5. Both total dry weights and fruit dry weights increased linearly with an increase in cumulative intercepted radiation. Overall RUE values for total dry matter accumulation by a tomato crop were on the order of 0.79-0.89 g MJ^{-1}. Overall lower R-squared values with the use of thermal time may be related to extended periods of warm and overcast weather during the 1991 growing season (Appendix B, Table 1). Under these conditions, intercepted radiation is a more reliable indicator of potential fruit yield (respective R-squared values were 0.74 and 0.92, for thermal time and cumulative intercepted radiation). The general relationships between cumulative intercepted radiation and fruit yield outlined here could be used to predict fruit yield based on radiation and LAI values only. The Mean Square Sum of Prediction (MSEP) could then be used to make inferences about the ability of the CROPGRO model to predict tomato fruit yield (in comparison to the simple linear relationship presented here) for a number of locations and growing seasons.

CHAPTER 4
EFFECTS OF WATER STRESS ON TOMATO GROWTH

Introduction

During the evaluation of growth and yield for a given crop in a specific production environment, it may be useful to outline production factors that cause deviations from potential yield. Potential yield can be defined as the yield attained for a crop with a closed crop canopy under optimal soil-bound factors (no pronounced water or nutrient stress) and in the absence of growth-reducing factors (such as pests and disease). Under these conditions crop development and yield are controlled by temperature and radiation only. Subsequently, effects of water, N, and P supply on plant growth can be evaluated (Goudriaan and van Laar, 1994). In the approach presented below, the effects of water stress on the growth and yield of tomato will be outlined based on compiled results for irrigation studies obtained from the literature. This analysis is complemented with results for an irrigation study conducted at Gainesville during the spring of 1996. During this study, the effects of water stress on photosynthesis, plant growth, and fruit yield were measured.

The primary objectives of this chapter are to (1) determine the effects of water stress on photosynthesis, canopy development, and plant growth; (2) evaluate the effects

of water supply on fruit yield and fruit quality; and (3) define functional relations that will outline the effects of water stress on plant growth and biomass accumulation over time.

Materials and Methods

Yield response to irrigation water for tomato was obtained from the literature for a number of production regions throughout the world. It was observed that fruit yield was affected by both irrigation-water supply and rainfall. As a result, differences in rainfall patterns between years (for the same location) and between locations often "masked" irrigation treatment effects, making it generally impossible to determine yield response to irrigation water supply directly. To address this problem, a yield-response curve to irrigation water supply was generated by the author through analysis of a limited number of data sets throughout the world which had: a) a cumulative rainfall < 70 mm; and b) a potential fruit yield > 60 t ha^{-1}; and which c) based irrigation supply on pan evaporation. For this analysis it was assumed that yield response to irrigation water depth was linear (Vinten et al., 1985) until factors other than irrigation water supply become limiting to plant growth, resulting in a yield plateau (Bar-Yosef and Sagiv, 1982). This approach resulted in the following yield response equation:

$$Y = a + bI \quad (\text{for } 0 \leq I < I_{max}) \text{ and } Y = Y_{max} \ (\text{for } I \geq I_{max}) \qquad (1)$$

where: Y = tomato fruit yield, a = x-axis intercept, b = yield increment due to irrigation water supply (t fruit [mm irrigation water]$^{-1}$), I = irrigation water depth (mm), Y_{max} =

potential fruit yield (t ha^{-1}), and I_{max} = minimum irrigation requirement to attain potential yield (mm). An overview of the data sets used for this analysis is presented in Table 4-1.

For the evaluation of data sets with rainfall >70 mm, it was assumed that the value of b (yield increment in response to irrigation water depth) was not affected by rainfall, and that rainfall affected only the values of "a" and "I_{max}". Subsequently, a correction factor was introduced by which rainfall was multiplied in order for yield data to match the x-intercept of the curve generated during the first part. This correction factor was termed the rainfall efficiency coefficient (REC). Rainfall was then multiplied by the REC, and this number was added to the actual irrigation water depth in order to estimate the amount of total water supply.

A similar approach was used for those trials for which irrigated was initiated at tensiometer readings of 10 cb. With the use of these tensiometer-controlled irrigation systems, irrigation water use efficiency (WUE) was about twice that of systems where irrigation scheduling was based on pan evaporation (Smajstrla and Locascio, 1996). As a result, a new value of "b" first needed to be determined. This was done by averaging initial yield increments for seven data sets collected at Gainesville during the 1989, 1990, and 1992 growing seasons. No yield response to irrigation water was observed during the 1991 growing season, due to excessive rainfall (Smajstrla and Locascio, 1996). Therefore, this data set was not included during calculation of the slope for the yield-response curve. Values of REC were determined for the different data sets using the same approach as outlined above, with fitted REC values being presented in Table 4-2.

The limitation of the approach outlined above is that both yield levels and irrigation

Table 4-1. Overview of data sets used to produce the yield-response curves for tomato (irrigation supply was based on pan evaporation).

Location	Year	Rainfall (mm)	Cultivar		REC [2]	Key	Reference
Rainfall < 75 mm							
Hawaii	1972	67	--	(FM)[1]	--	H72	Sammis and Wu, 1986
Israel	1977	0	Hosen Eilon	(FM)	--	R77	Bar-Yosef and Sagiv, 1982
Italy	1993	74	Pomo Red	(FM)	--	I93	Perniola et al., 1994
Quincy (FL)	1988	0	Walter	(FM)	--	Q88	Rhoads, 1990
S-Africa	1987	0	Flora Dade	(FM)	--	S87	Fischer and Nel, 1990
Rainfall > 75 mm							
G'ville (FL)	1988	118	Sunny	(FM)	1.80	G88a	Locascio and Smajstrla, 1989
G'ville (FL)	1989	199	Sunny	(FM)	0.90	G89b	Smajstrla and Locascio, 1990
G'ville (FL)	1990	306	Sunny	(FM)	0.30	G90b	Smajstrla and Locascio, 1990
G'ville (FL)	1990	346	Sunny	(FM)	0.40	G90e	Locascio and Smajstrla, 1996
G'ville (FL)	1991	508	Sunny	(FM)	0.90	G91e	Locascio and Smajstrla, 1996
G'ville (FL)	1992	259	Sunny	(FM)	0.90	G92e	Locascio and Smajstrla, 1996
Quincy (FL)	1988	125	Walter	(FM)	0.25	Q88	Rhoads, 1990
Quincy (FL)	1989	297	Walter	(FM)	0.25	Q89	Rhoads, 1990
Quincy (FL)	1990	170	Solarset	(FM)	0.90	Q90	Olson and Rhoads, 1992
Quincy (FL)	1991	218	Solarset	(FM)	0.90	Q91	Olson and Rhoads, 1992
Alabama	1971	475	Homestead24	(FM)	0.60	A71	Doss et al., 1975
Alabama	1972	300	Homestead24	(FM)	1.00	A72	Doss et al., 1975
Alabama	1973	470	Tropic	(FM)	0.70	A73	Doss et al., 1975
S-Carolina	1980	328	Tempo	(FM)	0.55	S80	Camp et al., 1989
S-Carolina	1981	490	Flora Dade	(FM)	0.40	S81	Camp et al., 1989
S-Carolina	1982	640	Tempo	(FM)	0.40	S82s	Camp et al., 1991
S-Carolina	1982(F)	403	Walter	(FM)	0.70	S82f	Camp et al., 1991
S-Carolina	1983	436	Sunny	(FM)	0.20	S83s	Camp et al., 1991
S-Carolina	1983(F)	294	Walter	(FM)	0.55	S83f	Camp et al., 1991

[1] FM: Fresh-market tomato; PR: Processing tomato

[2] REC: Rainfall efficiency coefficient

supply may vary between locations and years. It is thus preferable to express yield as a fraction of maximum yield and to define this relative yield as a function of relative evapotranspiration (ET). With the use of both relative ET and relative crop-growth

Table 4-2. Overview of data sets used to generate yield-response curves for tomato (irrigation supply was based on tensiometer readings)

Location	Year	Rainfall (mm)	Cultivar	REC [2]	Key	Reference
G'ville (FL)	1989	199	Sunny	0.32	G89b	Smajstrla and Locascio, 1990
G'ville (FL)	1990	306	Sunny	0.10	G90b	Smajstrla and Locascio, 1990
G'ville (FL)	1990	476	Sunny	0.11	G90c	Smajstrla and Locascio, 1996
G'ville (FL)	1990	346	Sunny	0.15	G90e	Locascio and Smajstrla, 1996
G'ville (FL)	1991	526	Sunny	0.27	G91c	Smajstrla and Locascio, 1995
G'ville (FL)	1991	508	Sunny	0.28	G91e	Locascio and Smajstrla, 1996
G'ville (FL)	1992	425	Sunny	0.13	G92c	Smajstrla and Locascio, 1996
G'ville (FL)	1992	295	Sunny	0.17	G92d	Smajstrla and Locascio, 1994
G'ville (FL)	1992	425	Sunny	0.30	G92e	Locascio and Smajstrla, 1996
G'ville (FL)	1993	325	Sunny	0.00	G93c	Smajstrla and Locascio, 1996

[2] REC: Rainfall efficiency coefficient

values, it became possible to combine the results for different locations and growing seasons. For this approach the following equation was used:

$$\frac{Y_a}{Y_m} - \frac{ET_a}{ET_m} \qquad (2)$$

where: Y_a = actual yield, Y_m = maximum yield, Et_a = actual evapotranspiration, and Et_m = maximum evapotranspiration. Relative yield values (Ya/Ym) for fruit yield, fruit number, fruit weight, stover dry weight, fruit dry weight, and total biomass were plotted as a function of relative evapotranspiration (Eta/ETm) for a number of data sets covering a range of growing conditions. Overall yield responses to relative ET were calculated using linear regression (Pitts and Obreza, 1996). In addition to this, growth reduction due to water stress could be expressed using the following equation:

$$(1 - \frac{Y_a}{Y_m}) - ky\ (1 - \frac{ET_a}{ET_m}) \qquad (3)$$

where ky = yield response factor (Doorenbos and Kassam, 1986). Values of ky were calculated using linear regression, assuming zero intercept.

An irrigation experiment involving the commercial tomato cultivar "Agriset 761" was conducted at the Horticultural Unit of the University of Florida in Gainesville during the spring of 1996. Tomato transplants were planted on March 29. Beds tops were 90 cm wide and were covered with 0.038 mm thick black polyethylene mulch. Bed spacing was 1.83 m and plant spacing within the row was 0.45 m. Double-wall drip tubing (Chapin Twinwall, Watertown, NY), with emitters spaced 0.31 m apart and a delivery rate of 62 mL m^{-1} h^{-1}, was placed 0.1 m from the bed center. Irrigation supply was cut off in border plots 14, 35, and 56 days after transplanting. Plants then were sampled 14, 35, 56, and 94 days after transplanting, with these data being used for growth analysis. Starting five weeks after transplanting, soil samples at depths of 0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm were taken along a cross-section of the bed between two plants at 15, 30, 45, 60, and 75 cm spacings from the edge of the bed.

Leaf photosynthesis of eight recently matured, sunlit leaves (PAR>1500 μE m^{-2} s^{-1}) was measured 45 days after transplanting for the first two irrigation cut-back treatments (CB1 and CB2), and for the control plots, using a Li-Cor 6200 Portable Photosynthesis System (Li-Cor, Inc., Lincoln, NE). Leaf water potential was measured 46 days after transplanting between 11 a.m. and 1 p.m. using a pressure bomb (Soil Moisture Equipment Corp, Model 3005, Santa Barbara, CA). The relative water content (RWC) of selected leaves was calculated using the relation

$$RWC = \frac{FW - DW}{TW - DW} \qquad (4)$$

where FW= fresh weight; DW= oven dry weight; TW= turgid weight (weight after floating the leaves on water for four hours). Plant tissue samples where dried at 65°C prior to dry weight determination, and followed by grinding and elemental analysis.

Results and Discussion

Analysis of Experimental Results Documented in the Literature

An overview of general yield and growth response to irrigation water supply and/or evapotranspiration for data sets obtained from the literature is presented in Table 4-3. The use of quadratic functions implies that after an (initial) linear response to irrigation water, the subsequent response to additional irrigation supply water decreases. Yield reduction may occur when irrigation-water supply exceeds the amount of water required for optimal growth (typically if $I > 0.75$-1.0 pan evaporation). This is most likely related to the leaching of nutrients (Locascio and Smajstrla, 1996) and the detrimental effects of excessive soil moisture content on plant growth. If yield response is linked to irrigation water supply (I) and total water supply (P+I), the y-intercepts (fruit yield) appear to be positive and negative, respectively. It should be noted that the inclusion of rainfall only affects the value of the intercept, with the overall slopes of yield response to irrigation (for linear equations) not being affected by rainfall. The negative y-intercept values for marketable fruit imply that tomato plants require a minimum amount of irrigation water

Table 4-3. Growth and yield response to irrigation water supply (absolute values).

Location	Year	Type	Regression equation	r^2	Reference
Fresh fruit yield (t ha^{-1})					
Canada	1979	PR	$Y = 15.8 + 0.33\ (P+I) - 0.00045(P+I)^2$	0.82	Tan, 1993
Canada	1979	PR	$Y = -26.3 + 0.30\ ET'$	0.71	Tan, 1993
Gaineville (FL)	1990	FM	$Y = 34.0 + 0.14\ I$	0.97	Locascio and Smajstrla. 1996
Gaineville (FL)	1990	FM	$Y = -12.7 + 0.14\ (P+I)$	0.97	Locascio and Smajstrla. 1996
Gaineville (FL)	1992	FM	$Y = 44.4 + 0.23\ I - 0.00043I^2$	0.98	Locascio and Smajstrla. 1996
Gaineville (FL)	1992	FM	$Y = -44.7 + 0.46(P+I) - 0.00043(P+I)^2$	0.98	Locascio and Smajstrla. 1996
Immokalee (FL)	1993	FM	$Y = 10.0 + 0.16\ I$	0.98	Obreza et al., 1996
Immokalee (FL)	1993	FM	$Y = -30.1 + 0.16\ (P+I)$	0.98	Obreza et al., 1996
Quincy (FL)	1991	FM	$Y = 26.2 + 0.15\ I - 0.0002\ I^2$	0.98	Olson and Rhoads, 1992
Quincy (FL)	1991	FM	$Y = -6.0 + 0.22\ (P+I) - 0.0002\ (P+I)^2$	0.98	Olson and Rhoads, 1992
Fresno (CA)	1980	PR	$Y = -6.7 + 0.21\ ET'$	0.97	Sanders et al., 1989a
Israel	1969	PR	$Y = 5.4 + 0.25\ I$	0.97	Vinten et al, 1985
Israel	1969	PR	$Y = -15.0 + 0.24\ (I+S)$	0.99	Vinten et al, 1985
Italy	1980	FM	$Y = -29.3 + 0.23\ ET'$	0.91	Quaglietta-Chiaranda and Zerbi; 1981
Dry matter (t ha^{-1})					
Fruit					
Fresno (CA)	1980	PR	$Y = 0.5 + 0.010\ ET'$	0.98	Sanders et al., 1989a
Stover					
Israel	1969	PR	$Y = 2.7 + 0.014\ I$	0.73	Vinten et al, 1985
Biomass					
Italy	1980	FM	$Y = 0.02 + 0.019\ ET'$	0.83	Quaglietta-Chiaranda and Zerbi; 1981

FM= fresh-market tomato; PR= processing tomato; I = irrigation; (P+I) =irrigation + rainfall ; ET'= estimated ET; S=soil storage

for vegetative growth before they can form marketable fruits. Intercepts of total plant dry weight and fruit dry weight plotted vs ET, on the other hand, typically have values close to zero (Table 4-3).

Under typical Florida production conditions, water supply from rainfall and/or moisture redistribution within the soil profile may be adequate to attain 35-100% of the yield potential of tomato (Locascio and Smajstrla, 1996; Olson and Rhoads, 1992). However, due to uneven rainfall distribution during the production season and the typically low moisture-storage capacities of soils commonly found in Florida, additional

irrigation is still required for optimum yields (Locascio and Smajstrla, 1996). Under these conditions, irrigation is applied to minimize water stress and to ensure the consistent high yields and high fruit quality required for commercial tomato production.

The yield of drip-irrigated tomato in response to irrigation water supply for locations with rainfall below 70 mm is shown in Fig. 4-1. The overall water use efficiency (WUE) for drip-irrigated tomato is on the order of 0.2 ton fresh fruit weight per mm of irrigation water supplied. This translates into a WUE value of 5 t acre-in^{-1}, and is about twice as high as for non-mulched furrow-irrigated crops (Doorenbos and Kassam, 1986). However, incidence of pests and disease may reduce fruit yield, resulting in values of 1.5 to 3.0 t acre-in^{-1} for drip-irrigated crops (Obreza et al., 1996).

Using non-linear regression analysis (SAS Institute, Cary, NC), the yield plateau

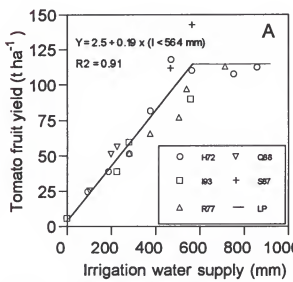


Fig. 4-1. Yield response of tomato to irrigation water supply for locations with rainfall <70 mm. The linear equation expressess fruit yield (y) as a function of irrigation depth (x). Legends are as outlined in Table 4-1.

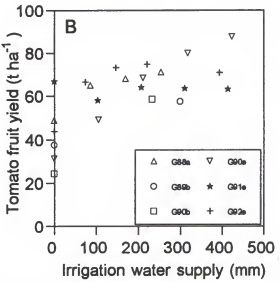


Fig. 4-2. Yield response of tomato to irrigation water supply at Gainesville for the 1988, 1989, 1990, 1991, and 1992 growing seasons. Legends are as outlined in Table 4-1.

was calculated to occur if I > 564 mm, corresponding to tomato fruit yields of 110 t ha^{-1}. With an irrigation-water supply greater than 564 mm, and in the absence of biotic stress and unfavorable soil conditions, fruit yields thus approach potential yield. An optimal irrigation supply of 564 mm, for locations with rainfall below 70 mm, falls within the range of 400-600 mm of seasonal water requirement for tomato as listed by Doorenbos and Kassam (1986). For locations with rainfall greater than 70 mm, differences between locations and production seasons were more pronounced, and yield response to irrigation water supply changed as rainfall increases (Camp et al., 1991; Locascio and Smajstrla, 1996). In Fig. 4-2, the yield response to irrigation water supply for five consecutive years is shown for Gainesville. Yield levels with no additional irrigation supply ranged from 25 to 65 t ha^{-1}. It thus appears that, to evaluate the effects of irrigation water supply on fruit yield for more humid regions, rainfall must be included in the analysis of results of irrigation trials.

In order to compare the contribution of rainfall to total crop water requirements for more humid regions, the use of a rainfall efficiency coefficient (REC) was introduced. With the use of this empirical coefficient, water use by the crop from water sources other than irrigation water can be estimated. This makes it possible to compare yield response to irrigation for different locations and seasons without developing a complete water balance. This method appears to work well as long as an approximate WUE value can be determined based on the initial yield response to irrigation supply. Results for four locations in the southeastern United States are shown in Fig. 4-3a through 4-3d. Estimated REC values are shown in Table 4-1.

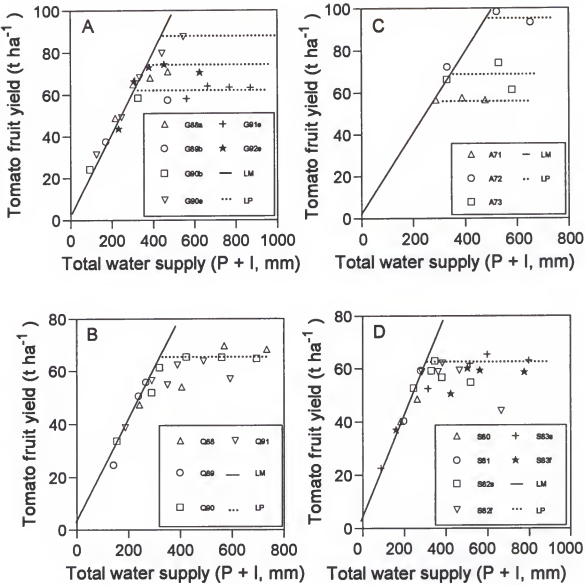


Fig. 4-3. Yield response of tomato to total water supply at a) Gainesville for the 1988, 1989, 1990, 1991, and 1992 growing seasons; b) Quincy for the 1989, 1990, and 1991 growing seasons; c) Auburn, Alabama for the 1971, 1972, and 1973 growing seasons; and d) Charleston, South Carolina for the 1980, 1981, 1982, and 1983 growing seasons; plotted in conjugation with a general linear regression model (LM) and linear plateau (LP) values. Values of fitted rainfall efficiency coefficients and legends are as outlined in Table 4-1.

Typically, REC values were on the order of 0.3-0.8, which implies that rainfall is less effective than irrigation water in meeting crop water requirements. From the exceptionally high REC value for the 1988 growing season at Gainesville, it may be concluded that, in some cases, water supply from the shallow water table underlying the production beds may have been appreciable. This is in agreement with findings by Vellidis et al. (1990), who reported that up to 34% of the crop water needs can be supplied from a shallow water table at this site. Assuming that the WUE of rainfall was similar to that of overhead irrigation, and by comparing the WUE values of overhead vs drip irrigation for mulched tomato, Rhoads (1990) estimated that REC values were on the order of 0.25. However, Smajstrla and Locascio (1996) stated that small rainfall events are fairly ineffective in meeting the crop water requirements of mulched tomato. It thus appears that REC values may be higher for larger rains which permit both lateral and capillary flow under the mulch into the plant beds; this may result in higher overall REC values.

Assuming a value of 0.19 t mm^{-1} for the WUE appeared to fairly closely match the yield response to irrigation water for most locations tested. However if, due to excessive rainfall, no measurable initial yield increase due to irrigation water supply occurred, it was no longer possible to estimate either REC or WUE values (e.g. Fig. 4-3c, legend: A71). The yield plateaus drawn in Fig. 4-3 are indicative of "attainable" yields for specific locations and production systems. In a number of cases these yields were relatively low compared to the potential yields reported earlier. It may be concluded that, in addition to the lack of response to irrigation treatments (Fig 4-2, legend: G91e) in this region, overall fruit yields may be reduced due to lower radiation values, increased relative humidity, and

the excessive soil moisture levels typically associated with more extensive rainfall. This can result in a decrease in assimilate supply to the fruits, poor fruit-set, and increased incidence of diseases that are commonly observed during the second part of the growing season in the southeastern United States.

The average WUE value for the tensiometer-controlled irrigation trials conducted at Gainesville was 0.39 t fruit mm^{-1} (9.9 t acre-in^{-1}) (Fig. 4-4). With the use of tensiometer-controlled drip systems, similar or higher yields can thus be attained with about half the amount of water required when irrigation is based on pan evaporation (Smajstrla and Locascio, 1996). Due to the higher value of WUE for tensiometer-controlled systems, values of REC dropped appreciably (Table 4-2). This decrease in the efficiency of rainfall to meet the water requirements of the crop is most likely due to an

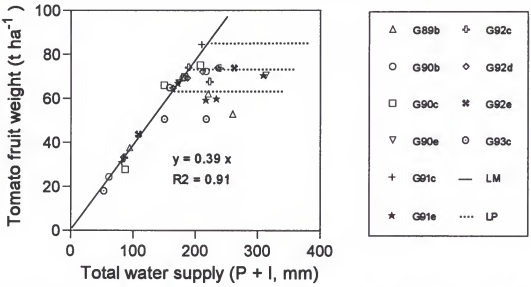


Fig. 4-4. Yield response of tomato to total water supply at Gainesville for tensiometer-controlled drip-irrigated crops for the 1989, 1990, 1991, 1992, and 1993 growing seasons plotted against a fitted linear regression model (LM) that expresses fruit yield (y) as a function of total water supply (x). Values of fitted rainfall efficiency coefficients and legends are as outlined in Table 4-2.

increase in WUE. A doubling of the WUE values will reduce REC values by 50%. This implies that rainfall is only relatively less effective in meeting crop water requirements. However, since total seasonal water use is reduced from about 500 to 250 mm, rainfall may still contribute an appreciable fraction of the total water use. The reduction in REC values may also be attributed to the drying of the edges of the bed and subsequent reduced root growth near the edges. As a result, smaller rainfall events no longer would contribute to moisture supply for the crop. Lower irrigation rates could also result in a drop in the water table, further decreasing capillary redistribution of rainfall.

In the next section, effects of relative evapotranspiration (Eta/ETm) on relative plant growth processes (Ya/Ym) will be presented. Using this approach, it becomes possible to combine results for different yield levels. The use of relative evapotranspiration instead of irrigation water supply also appears to be preferable, since it is a more direct indicator of water stress than is irrigation water depth. Plant growth and yield relationships for individual data sets were calculated from yield values obtained from the literature, and are outlined in Table 4-4. In this table, relative plant growth values (y) are expressed as a function of estimated values of ET (ET').

Typically, ET values were not measured directly, but were obtained by using empirical relations to estimate ETm based on pan evaporation values (Perniola et al., 1994; Sammis and Wu, 1986; Sanders et al., 1989a; Yrrisary et al., 1993). In other cases, estimated values of ETm were based on data from plants grown in lysimeters (Giardini et al, 1988a,b Tan, 1993; Vinten et al, 1985). In order to derive overall relationships for the effects of water stress on plant weight, results from individual studies were combined,

Table 4-4 Growth and yield response to irrigation water supply (relative values).

Location	Year	Type	Regression equation	r^2	Key	Reference
Fruit yield t ha^{-1}						
Canada	1979-82	PR	Y = - 0.37 + 1.29 ET'	0.71	C79	Tan, 1993
Fresno (CA)	1980	PR	Y = - 0.07 + 1.01 ET'	0.97	F80	Sanders et al., 1989a
Gainesville (FL)	1992	FM	Y = 0.03 + 1.04 ET'	0.93	G92	Smajstrla and Locascio, 1994
Hawaii	1972	FM	Y = - 0.13 + 1.05 ET'	0.95	H72	Sammis and Wu, 1986
Italy	1978	PR	Y = - 0.05 + 1.12 ET'	0.90	I78	Giardini et al., 1988a
Italy	1980	FM	Y = - 0.27 + 1.16 ET'	0.91	I80	Quaglietta-Chiaranda and Zerbi, 1981
Italy	1983-84	PR	Y = - 0.09 + 0.98 ET'	0.92	I83	Giardini et al., 1988b
Italy	1993	FM	Y = - 0.03 + 1.04 ET'	0.99	I93	Perniola et al., 1994
Quincy (FL)	1990-91	FM	Y = 0.26 + 0.77 ET'	0.96	Q90	Olson and Rhoads,1992
Israel	1969	PR	Y = -0.09 + 1.14 ET'	0.93	R69	Vinten et al., 1985
Spain	1991	PR	Y = - 0.24 + 1.32 ET'	0.91	S91	Yrrisarry et al., 1993
Fruit number						
Fresno (CA)	1980	PR	Y = 0.22 + 0.75 ET'	0.99	F80	Sanders et al., 1989a
Gainesville (FL)	1992	FM	Y = 0.08 + 0.99 ET'	0.89	G92	Smajstrla and Locascio, 1994
Italy	1978	PR	Y = 0.16 + 0.78 ET'	0.89	I78	Giardini et al., 1988a
Italy	1980	FM	Y = - 0.27 + 1.20 ET'	0.92	I80	Quaglietta-Chiaranda and Zerbi, 1981
Quincy (FL)	1990-91	FM	Y = 0.35 + 0.69 ET'	0.80	Q90	Olson and Rhoads,1992
Spain	1991	PR	Y = - 0.24 + 1.32 ET'	0.91	S91	Yrrisarry et al., 1993
Fruit size						
Fresno (CA)	1980	PR	Y = 0.57 + 0.45 ET'	0.89	F80	Sanders et al., 1989a
Gainesville (FL)	1992	FM	Y = 0.53 + 0.51 ET'	0.87	G92	Smajstrla and Locascio, 1994
Italy	1978	PR	Y = 0.69 + 0.33 ET'	0.37	I78	Giardini et al., 1988a
Italy	1980	FM	Y = - 0.36 + 1.28 ET'	0.79	I80	Quaglietta-Chiaranda and Zerbi, 1981
Italy	1983	PR	Y = - 0.19 + 1.15 ET'	0.97	I83	Giardini et al., 1988b
Quincy (FL)	1990-91	FM	Y = 0.65 + 0.37 ET'	0.76	Q90	Olson and Rhoads,1992
Spain	1991	PR	Y = 0.06 + 0.98 ET'	0.80	S91	Yrrisarry et al., 1993
Dry Matter Yield t ha^{-1}						
Fruit						
Fresno (CA)	1980	PR	Y = 0.10 + 0.87 ET'	0.98	F80	Sanders et al., 1989a
Italy	1978	PR	Y = 0.03 + 1.05 ET'	0.90	I78	Giardini et al., 1988a
Italy	1983-84	PR	Y = 0.13 + 0.89 ET'	0.90	I83	Giardini et al., 1988b
Spain	1991	PR	Y = 0.10 + 0.86 ET'	0.94	S91	Yrrisarry et al., 1993
Stover						
Italy	1993	FM	Y = 0.17 + 0.92 ET'	0.88	I93	Perniola et al., 1994
Italy	1993	FM	Y = 0.21 + 0.77 ET'	0.87	I93	Perniola et al., 1994
Italy	1978	PR	Y = 0.52 + 0.45 ET'	0.71	I78	Giardini et al., 1988a
Spain	1991	PR	Y = 0.24 + 0.77 ET'	0.99	S91	Yrrisarry et al., 1993
Biomass						
Italy	1978	PR	Y = 0.23 + 0.81 ET'	0.95	I78	Giardini et al., 1988a
Italy	1983-84	PR	Y = 0.01 + 0.92 ET'	0.92	I83	Giardini et al., 1988b
Italy	1993	FM	Y = 0.06 + 0.88 ET'	0.96	I93	Perniola et al., 1994
Italy	1980	FM	Y = 0.02 + 0.90 ET'	0.83	I80	Quaglietta-Chiaranda and Zerbi, 1981
Spain	1991	PR	Y = 0.16 + 0.82 ET'	0.99	S91	Yrrisarry et al., 1993

FM= Fresh-market tomato; PR= Processing tomato; ET'= estimated ET;

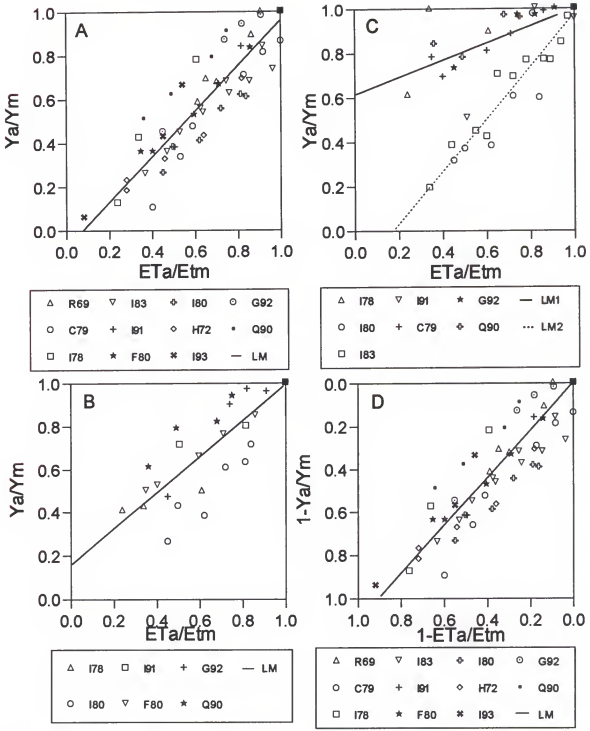


Fig. 4-5. Relationship between relative yield (Ya/Ym) and relative evapotranspiration (Eta / ETm) for a) tomato fruit yield; b) fruit number; and c) average fruit size ; and d) relationship between relative fruit yield decrease (I-Ya/Ym) and relative evapotranspiration deficit (1-Eta/ETm); Linear models express relative yield (y) as a function of relative evapotranspiration (x). Legends and regression models are as outlined in Tables 4-4 and 4-5, respectively.

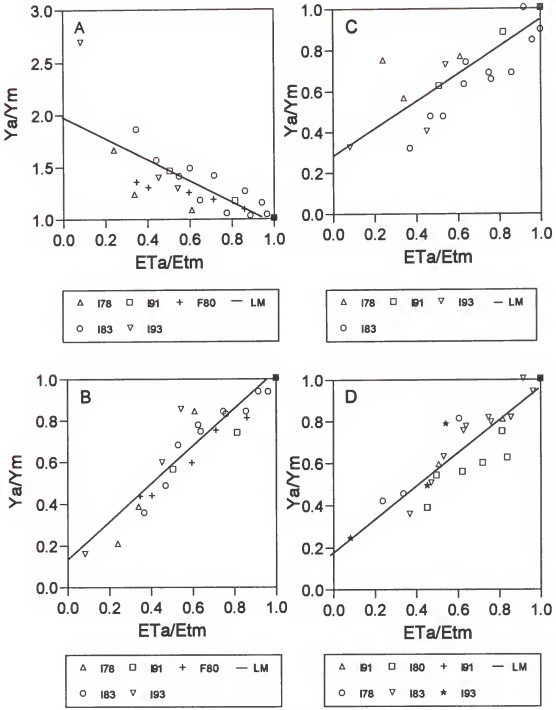


Fig. 4-6. Relationship between relative yield (Ya/Ym) and relative evapotranspiration (ETa/ETm) for a) fruit dry matter content; b) fruit dry weight; c) vegetative dry weight; and d) total dry weight; Linear models express relative yield (y) as a function of relative evapotranspiration (x). Legends and regression models are as outlined in Tables 4-4 and 4-5, respectively.

with overall relationships being presented in Table 4-5 and plotted in Figs. 4-5 and 4-6. In a number of cases relative yields did not approach unity at Eta/Etm values of unity (e.g. Fig. 4-5a). Alternatively, yield-response (Ky) factors were calculated using the same datasets but assuming zero intercepts (Fig. 4-5d). The advantage of this approach is that effects of water stress on plant growth are captured in a single coefficient instead of a regression equation, with relative values always being unity in the absence of water stress. In order to outline the effects of water supply on crop growth of tomato in comparison to peanut (Arachis hypogaea L.), crop coefficients and yield-response factors for both crops are outlined in Table 4-6.

Table 4-5 Growth and yield response to irrigation water supply (averaged values)

Variable	Regression equation	r^2	ky	r^2
Fruit fresh weight (FM)	-0.05 + 1.03 ET'	0.83	1.07	0.83
Fruit fresh weight (PR)	-0.10 + 1.06 ET'	0.88	1.15	0.87
Fruit fresh weight (overall)	-0.08 + 1.04 ET'	0.85	1.11	0.85
Fruit number	0.16 + 0.82 ET'	0.82	0.82	0.71
Fruit size (1)[1]	0.64 + 0.37 ET'	0.64	0.34	0.63
Fruit size(2)	-0.18 + 1.17 ET'	0.85	1.20	0.85
Fruit size (overall)	0.34 + 0.63 ET'	0.39	0.70	0.39
Dry matter content	1.97 - 1.02 ET'	0.62	-1.85	0.76
Fruit dry weight	0.12 + 0.90 ET'	0.89	0.87	0.89
Vegetative dry weight	0.27 + 0.66 ET'	0.68	0.79	0.63
Total dry weight	0.16 + 0.81 ET'	0.82	0.87	0.84

[1] Fruit size showed differential responses for two groups of data sets

Table 4-6 Overview of crop coefficients and yield-response factors for tomato and peanut

	Peanut			Tomato			
Growth period	Duration	kc [1]	ky [1]	Duration	kc[1]	kc[2]	ky
Establishment	10-20	0.40-0.50	0.2	25-35	0.40-0.50	0.20	0.4
Vegetative growth	25-35	0.70-0.80	0.2	20-25	0.70-0.80	0.45	0.4
Flowering	30-40	0.95-1.10	0.8	20-30	1.05-1.25	0.57	1.1
Yield formation	30-35	0.70-0.80	0.6	20-30	0.80-0.90	0.73	0.8
Ripening	10-20	0.55-0.60	0.4	15-20	0.60-0.65	0.59	0.4
Overall			0.7				1.05

[1] Source: Doorenbos and Kassam, 1986; kc= crop coefficient; ky= yield response factor;

[2] Source: Obreza et al., 1996

The calculated value of the yield response factor (ky) for fruit weight of fresh-market tomato was 1.07 (Table 4-6). This value compares favorably with the value of 1.05 reported by Doorenbos and Kassam (1986). Total fresh fruit weight appears to be more strongly affected by water stress than fruit dry weight (Table 4-5; Figs. 4-5a and 4-6b). This is most likely related to the increase in fruit dry matter content (Fig. 4-6a) commonly observed in water-stressed tomato plants. This is in agreement with reports by Adams and El-Gizawy (1986) and Mitchell et al. (1991). Yield decrease due to water stress appears to be caused by a decrease in both fruit number and average fruit size (Table 4-5; Figs. 4-5b and 4-5c). It was observed that effects of water stress on fruit number varied between two groups of data sets. For the first group, relative fruit size appeared to be relatively insensitive to water stress (Fig. 4-5c, solid line). However, for a second group, the decrease in fruit weight due to water stress was much more pronounced (Fig. 4-5c, dotted line). This differential response to water stress may be related to the method used to calculate average fruit weight. In previous studies it was observed that water stress resulted in an appreciable increase in the number of undersized fruits (Quaglietta-Chiaranda and Zerbi, 1981; Scholberg, 1992). Including these small fruits in calculation of the average fruit size can result in a much more pronounced decrease in average fruit size due to water stress, compared to values of average fruit size based on marketable fruit yield only. Vinten et al. (1985) reported that yield reductions of 70% due to water stress coincided with reductions in fruit number and fruit size by 65 and 25%, respectively. Based on this finding, a value of 0.34 for the yield-response factor for average fruit size appears to be appropriate.

In contrast to other variables tested, relative dry matter content increased as relative ET values decreased (Fig. 4-6a,) with assimilate supply to the fruit appearing to be less affected by water stress compared to water uptake by the fruit. These findings are in agreement with reports by Hsiao (1990). Stover dry weights appeared to be relatively less sensitive to water stress compared to fruit dry weight (Table 4-5; Figs. 4-6b and 4-6c). This may be related to increased flower abortion observed for water-stressed plants (Doorenbos and Kassam, 1986).

Irrigation Study (Gainesville, 1996)

The 1996 spring growing season at Gainesville was relatively dry. Total rainfall amounted to 293 mm, and the few heavy rainfall events were typically followed by fairly long dry spells (Fig. 4-7). Total irrigation depths during the growing season were 35, 77,

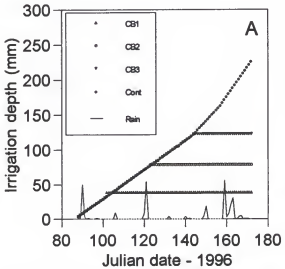


Fig. 4-7. Distribution of irrigation depths for the irrigation cutback treatments, and of daily rainfall, for the spring growing season at Gainesville, 1996.

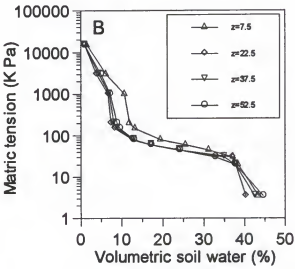


Fig. 4-8. Volumetric soil water release curve for the 7.5, 22.5, 37.5, and 52.5 cm soil depths. (z=7.5, 22.5, 37.5, and 52.5, respectively) of a Millhopper fine sand.

118, and 225 mm of irrigation for irrigation-cutback treatments one, two, three, and the control treatment, respectively (Fig. 4-7). Available soil moisture content for the Millhopper sand typically ranges from 9% for the top layer to 6% for the lower soil layers (Table 4-7). A soil moisture release curve for this soil is shown in Fig. 4-8. Lower available soil moisture percentages for the lower soil layers are most likely related to the lower organic matter and silt contents of these layers.

Results for effects of irrigation treatments on plant growth and fruit yield are shown in Table 4-8 and Fig. 4-9. Water stress during initial vegetative growth resulted in a reduction in the number of main-stem nodes formed (Table 4-8, cutback1: day 35). Leaf area was reduced by 35% and 25% if water stress was induced at two and five weeks after transplanting, respectively . However, if water stress was initiated at eight weeks (cutback3 treatment), no reduction in either leaf and stem weights occurred, and the reduction in biomass was mainly due to a reduction in fruit weight. Water stress resulted in a reduction of plant height, total leaf number, leaf size, the number of branches

Table 4-7. Soil characteristics for a Millhopper fine sand (loamy, siliceous, hyperthermic, Grossarenic Paleudults)

Depth	Water content (Vol%)				Ks [5]	Bulk dens.	Particle size dist.			Org. C
(cm)	P.W.P[1]	F.C.[2]	Sat.[3]	A.S.M[4]	(cm h^{-1})	(g cm^{-3})	sand	silt	clay	(%)
0 -15	1.6	10.7	43.4	9.1	9.3	1.50	91.6	6.3	2.1	1.2
15-30	1.0	6.7	40.3	5.7	24.4	1.55	93.6	4.1	2.3	0.4
30-45	1.0	7.0	42.5	6.0	27.7	1.56	94.0	3.7	2.4	0.3
45-60	1.0	7.2	44.6	6.2	31.9	1.57	94.3	3.3	2.4	0.2

[1] "Permanent wilting point": 15.0 bar
[2] "Field capacity": 0.1 bar
[3] "Saturation": 0.0035 bar
[4] Availablc soil moisture content
[5] Saturated hyraulic conductivity

Table 4-8. Summarized growth measurements, Gainesville irrigation trial, 1996.

Day	Node No.	LAI	Roots	Dry weight per plant (g) Stems	Blades	Fruit	Total
Cutback 1[1,2]							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
21	10.0 ± 0.6	0.06 ± 0.01		0.3 ± 0.03	0.5 ± 0.1		0.8 ± 0.1
35	15.0 ± 0.0	0.61 ± 0.10		16.4 ± 1.6	21.5 ± 3.0	0.4 ± 0.3	38.2 ± 4.5
56	19.0 ± 1.0	1.52 ± 0.17		67.8 ± 7.0	62.3 ± 7.1	81.3 ± 6.9	211 ± 20.5
94	20.0 ± 0.0	1.69 ± 0.12		89.6 ± 1.6	83.1 ± 5.2	272 ± 16.9	445 ± 17.3
Cutback 2							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
14	10.0 ± 0.6	0.06 ± 0.01		0.3 ± 0.03	0.5 ± 0.1		0.8 ± 0.1
35	16.7 ± 0.7	0.71 ± 0.03		19.1 ± 1.1	23.2 ± 1.4	0.7 ± 0.3	43.0 ± 2.5
56	16.7 ± 0.7	1.66 ± 0.11		82.4 ± 1.9	64.9 ± 1.3	52.9 ± 11.5	200 ± 12.0
94	18.0 ± 0.0	1.96 ± 0.25		112 ± 7.4	87.5 ± 2.1	253 ± 32.2	455 ± 40.1
Cutback 3							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
14	10.0 ± 0.6	0.06 ± 0.01		0.3 ± 0.03	0.5 ± 0.1		0.8 ± 0.1
35	16.7 ± 0.7	0.71 ± 0.03		19.1 ± 1.1	23.2 ± 1.4	0.7 ± 0.3	43.0 ± 2.5
56	16.3 ± 0.3	2.11 ± 0.27		108 ± 12.2	75.5 ± 7.1	72.2 ± 9.0	255 ± 21.5
94	19.0 ± 0.6	2.59 ± 0.17		142 ± 4.1	112 ± 9.6	295 ± 30.7	558 ± 43.0
Control							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
14	10.0 ± 0.6	0.06 ± 0.01		0.3 ± 0.03	0.5 ± 0.1		0.8 ± 0.1
35	16.7 ± 0.7	0.71 ± 0.03		19.1 ± 1.1	23.2 ± 1.4	0.7 ± 0.3	43.0 ± 2.5
56	16.3 ± 0.3	2.11 ± 0.27		108 ± 12.2	75.5 ± 7.1	72.2 ± 9.0	255 ± 21.5
94	18.0 ± 1.6	2.63 ± 0.11		139 ± 4.1	99.3 ± 7.5	368 ± 2.8	610 ± 18.3

[1] Values are averages of 3 replicates

[2] Irrigation water supply was cut off 2, 5, and 8 weeks after transplanting for cutback treatments 1, 2, and 3, respectively

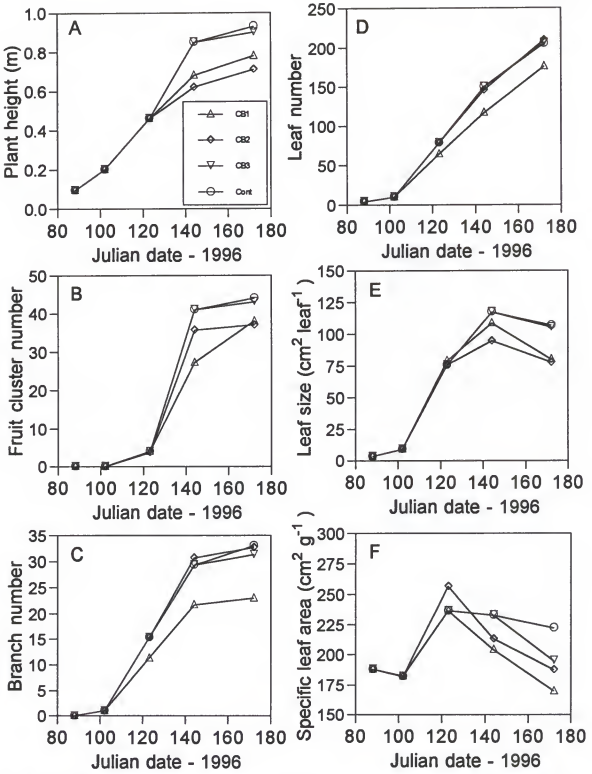


Fig. 4-9. Effects of irrigation treatments for the Gainesville 1996 growing season on a) plant height; b) branch number; c) fruit cluster number; d) leaf number; e) average leaf size; and f) specific leaf area (SLA);

and fruit clusters (Fig. 4-9). Similar results were reported by Giardini et al. (1988a). The incidence of water stress also resulted in thickening of the leaves, thus resulting in reduced specific leaf area values (Fig. 4-9f).

Water stress resulted in an appreciable decrease in leaf conductance, leaf photosynthesis, leaf water potential, and relative water content of the leaves (Table 4-9). The reduction in photosynthesis due to water stress is in agreement with reports by Tan et al. (1981). The observed values for leaf water potential for irrigated and non-irrigated plants are similar to those reported by Perniola et al. (1994). In their work it was shown that a linear increase in leaf water potential from -1.9 to -0.7 MPa resulted in an exponential decrease in leaf resistance from 30 to 1 s cm^{-1} (corresponding leaf conductance values were 0.03 and 1 cm s^{-1}, respectively). The relatively high values for leaf conductance, water potential, and photosynthesis for the first irrigation cutback treatment seemed to indicate that these plants were fairly well-adjusted to the water stress.

Fruit yield and dry matter accumulation for the irrigation treatments are shown in Fig. 4-10. It was observed that fruit yield for three out of four treatments fell exactly on a common line. However, fruit yield for the cutback1 treatment was relatively high

Table 4-9. Summarized photosynthetic measurements, Gainesville irrigation trial, 1996 [1]

Treatment	Pg ($\mu M\ m^{-2}\ s^{-1}$)	Stomatal conductance ($cm\ s^{-1}$)	SLA ($cm^2\ g^{-1}$)	DM%	Ψ_{leaf} (-Mpa)	RWC
Cutback1	27.8 ± 1.9	1.20 ± 0.07	175.2 ± 5.6	21.0 ± 0.4	1.01 ± 0.04	0.82 ± 0.01
Cutback2	12.4 ± 1.4	0.47 ± 0.07	185.4 ± 3.6	22.3 ± 0.2	1.35 ± 0.05	0.81 ± 0.02
Control	29.5 ± 1.4	1.62 ± 0.08	182.9 ± 7.1	20.9 ± 0.3	0.71 ± 0.06	0.85 ± 0.01

[1] Measurements were taken 45 days after transplanting

compared to the other irrigation treatments. Water stress during initial growth resulted in more pronounced reduction in vegetative growth compared to fruit yield whereas, for the introduction of water stress during the second part of the growing season, the reverse was true (Fig. 4-10b).

The relatively large yield reduction due to water stress initiated at a later growth stage is in agreement with lower values of the yield-response factor during vegetative growth compared to flowering and yield formation (Table 4-6). The small effect of water stress initiated during the latter part of the growing season on vegetative growth, and the large reduction in fruit fresh weight shown in Fig. 4-10, are in agreement with findings by Mitchell et al. (1991). However, the reduction in fruit dry weight which they reported was only 5%, which appears to be small compared to the 19% observed here. In their study, water stress was gradually increased during a two-week period; this may have

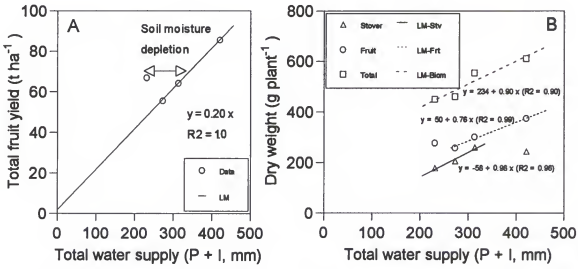


Fig. 4-10. Effects of irrigation treatments for the 1996 growing season at Gainesville on a) total fruit fresh weight; and b) stover dry weight, fruit dry weight, and total dry weight. The linear regression model (LM) expresses weight (y) as a function of total water supply (x), assuming a value of 0.67 for the rainfall efficiency coefficient.

resulted in a relatively smaller reduction in photosynthesis and in assimilate translocation to the fruit. Based on field observations during soil sampling, it appeared that an early onset of water stress in tomato resulted in increased root proliferation in lower soil layers. As a result, tomato plants may have increased water uptake from lower soil layers. This, along with the reduction in total leaf area, may have favored the overall water status of these plants, resulting in relatively high photosynthetic rates.

Average soil moisture contents for the 7.5, 22.5, 37.5, and 52.5 cm soil depths are shown in Fig. 4-11. The ending of irrigation water supply invariably resulted in a reduction of soil moisture content throughout the soil profile. However, this effect was most pronounced for the top 30 to 40 cm of the soil profile. Soil water depletion at greater soil depths was typically limited, except for the cutback1 treatment (Fig. 4-11d). Introducing water stress during the initial vegetative growth was reported to enhance root growth (Doorenbos and Kassam, 1986), resulting in increased water extraction from lower soil layers (Giardini et al., 1988a). This effect is illustrated by contour plots of soil moisture content for cross sections of tomato production beds as shown in Fig. 4-12. Introducing water stress during initial growth (cutback 1) resulted in increased water extraction at greater soil depths (Fig. 4-12a). The root system of cutback 2 appeared to be more shallow, with soil water depletion mainly occurring in the top 20 cm of the soil profile (Fig. 4-12b). With this treatment, the main soil moisture gradient was upward due to the predominance of capillary rise. The control treatment, on the other hand, showed a predominantly downward gradient. The oblong wetting patterns appear to be typical for coarse-textured soils irrigated with drip irrigation (Fig. 4-12c).

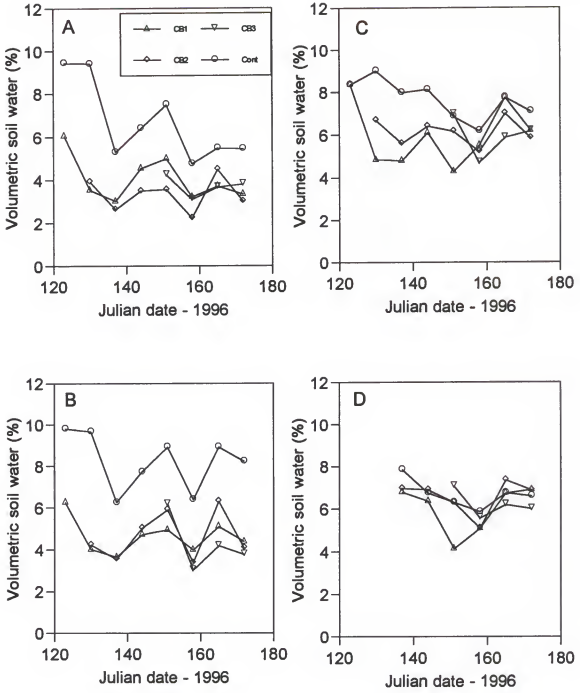


Fig. 4-11. Effects of irrigation treatments on volumetric water content at Gainesville during the 1996 growing season at soil depths of a) 7.5 cm; b) 22.5 cm; c) 37.5 cm; and d) 52.5 cm.

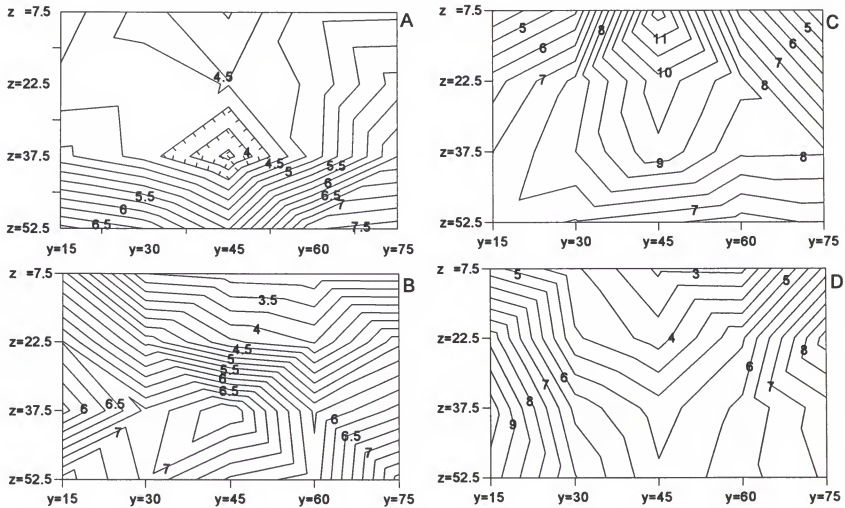


Fig. 4-12. Soil moisture-content contour plots for drip-irrigated production beds in irrigation cutback treatments a) CB1 (week 8); b) CB2 (week 8); Control (week 8); and CB3 (week 9). Contour lines show vulumetric water percentage of the soil.

Six days after introducing the last cutback treatment, a rainfall event of 58 mm occurred, with the soil moisture distribution 24 hours after the event being as shown in Fig. 4-12d. The downward gradient in the center of the bed is related to water extraction by the crop. Water infiltration from rainfall appeared to occur predominantly through subsurface lateral movement from the non-mulched center rows. These results are in agreement with the infiltration patterns discussed by Smajstrla and Locascio (1996).

Conclusions

Based on a detailed analysis of the literature, it was concluded that the WUE of drip-irrigated tomato was on the order of 0.19 t fruit mm^{-1} if irrigation scheduling was based on pan evaporation readings. However, with the use of tensiometer-controlled irrigation system, WUE was increased to about 0.39 t fruit mm^{-1}. It is further concluded that, for locations where rainfall is above 100 mm, contributions of rainfall to crop water requirements may be appreciable, and rainfall must therefore be included when evaluating the yield response to irrigation water. By introducing REC values, the contribution of rainfall to crop water requirements could be estimated. Based on the values for yield-response factors presented in Table 4-6, it may be concluded that tomato is more sensitive to water stress compared to peanut. Total crop water requirements are similar for both crops, but overall yield reduction due to water stress is 50% higher for tomato. The crop coefficients listed by Doorenbos and Kassam (1986) appear to be similar for both crops, but values outlined by these authors appear to be high in comparison to those listed by Obreza et al. (1996). Lower values for production systems in Florida may be related to

lower plant densities, and to increased water-use efficiency due to the use of drip irrigation and plastic mulch. The values for yield-response factors presented in Table 4-5 could be used in crop growth models to describe the effects of water stress on dry matter accumulation and fruit yield. Relative process rates could also be described as a function of soil water deficit (ratio between water uptake and ETm) in manner similar to that described by Johnson and Ritchie (1989).

Based on the results of the field experiment, it may be concluded that the timing and adjustment of plants to water stress can be of appreciable importance in the discussion of effects of water stress on plant growth. It should be noted that the discussion above is based on results from a single season's study. Though replication of this study is desirable, results for subsequent growing seasons may not be consistent due to differences in rainfall distribution (Locascio and Smajstrla, 1996). The prolonged dry spells between rainfall events and the below-average rainfall observed during this study should have resulted in a favorable environment in which to evaluate the effects of water stress on plant growth.

CHAPTER 5
EFFECTS OF NITROGEN-SUPPLY ON TOMATO GROWTH

Introduction

In addition to irrigation supply, commercial tomato production requires optimal fertilizer management for high yields and maximum profits. Because of the potential value of commercial crops and the relatively low cost of fertilizer, producers tend to overfertilize to minimize risk of yield reduction due to nutrient stress (Locascio et al., 1992).

In many cases N appears to be the element that is most limiting to crop growth, especially on coarse-textured soils of low organic matter content. Under typical Florida conditions, N is readily lost due to leaching and denitrification and, in most cases, N concentrations in the underlying groundwater drop to below 1 ppm by the end of the growing season (McNeal et al., 1994). Adequate supply of N in phase with crop N requirements is thus required to ensure optimal crop yields while minimizing the risk of N leaching and groundwater contamination (Hochmuth, 1988).

The effects of N-fertilizer rates on plant growth, N uptake, and N partitioning within the plant are discussed in the Results and Discussion section. Initially, a short overview of yield response of tomato to N-fertilizer supply as reported in the literature is outlined, along with a brief discussion of N management. This is followed by a discussion of N effects on dry matter accumulation, canopy characteristics, and photosynthesis based

on a number of field experiments. In a subsequent section, effects of N supply on N concentration in plant tissue material is presented. Finally, apparent nitrogen recovery rates and nitrogen use efficiencies are calculated. Soil N concentrations and a general discussion on the effects of N rate and cropping system on N dynamics in the soil are presented in Chapter 6.

Materials and Methods

Yield data for tomato over a range of fertilizer rates were obtained from the literature for locations throughout the world, and were fitted to quadratic regression models. Field experiments involving commercial tomato cultivar response to N were also conducted at Bradenton (1994 and 1995); Gainesville (1995 and 1996); Isabela Puerto Rico (1994); and Quincy (1995). An overview of crop management practices, N-fertilizer rates, and planting dates was presented in Table 3-1. A summary of weather data and soil profile descriptions for the locations involved is given in Appendix B, Table 1 through 8.

At each location plants were sampled at 2- or 3-week sampling intervals. A total of two to four plants were sampled destructively on each sampling date, and plant growth measurements were recorded as outlined in the section on general growth characteristics.

Partitioning of assimilates between plant organs was calculated by dividing weight increments for stems, leaves, and fruits by the total dry matter increment between two subsequent sampling dates. Leaf photosynthesis was measured for six recently matured, sunlit leaves (PAR>1500 $\mu E\ m^{-2}\ s^{-1}$) for Gainesville (1995 and 1996) and Quincy (1995) 49 days after transplanting using a Li-Cor 6200 Portable Photosynthesis System (Li-Cor,

Inc., Lincoln, NE). Plant tissue samples were dried at 65°C prior to dry weight determinations, followed by grinding. Plant samples were digested by adding 2.5 mL of 98% sulfuric acid and 1.0 g of potassium sulfate-catalyst mixture to 100 mg of plant tissue. Digestion tubes were heated in a digestion block to 380° C for 4 hours. After digestion, samples were diluted to 100 mL, and subsamples were transferred to 20 mL scintillation vials and stored at 5° C prior to analysis. Total N was determined using Rapid-Flow Analyzer (RFA) technology (ALPKEM Corporation, 1989). Nitrogen accumulation by the plant was calculated by multiplying tissue weights of root, stem, petiole, leaf, and fruit tissue by the corresponding N concentrations. Nitrogen partitioning between plant organs was calculated by dividing incremental N accumulation in stems, leaves, and fruits by the total N increment. N partitioning within the fruit was determined during the 1996 growing season in Gainesville for both the zero-N and the control (N=200 kg ha^{-1}) treatments. Twenty fruits were sliced into pieces and seeds were separated from the fruit pulp manually. After soaking for 48 hours, the seeds were rinsed, and dry weights and N concentration of both seeds and fruit pulp were determined separately.

Results and Discussion

Yield Response to N Fertilizer

Fertilizer recommendations for commercial tomato production may vary depending on the cropping system and soil characteristics. N-rates for high-yielding varieties are typically on the order of 100-150 kg N ha^{-1} (Doorenbos and Kassam, 1986).

Recommended N-rates for mineral soils in Florida currently average 195 kg N ha^{-1} (Maynard and Hochmuth, 1995). However, commercial rates typically range from 300 to 400 kg N ha^{-1} (McNeal et al., 1995). With the use of subirrigation, most of the fertilizer typically is applied preplant via one or two concentrated surface bands. With the use of drip irrigation on coarse-textured soils, on the other hand, the use of fertigation may be required. In this case only 20-25% of the fertilizer is applied preplant, with the remainder being supplied via the irrigation water (Maynard and Hochmuth, 1995).

An overview of yield response to N fertilizer for tomato is presented in Table 5-1. In the absence of additional N supply, fruit yields were typically on the order of 20 to 40 t ha^{-1} and 40-70 t ha^{-1} for coarse- and medium-textured soils, respectively. It could be hypothesized that fine-textured soils are less prone to N-leaching and, therefore, will sustain higher residual soil N values.

With efficient use of both water and nutrients, fruit yields on the order of 90 t ha^{-1} can be attained with as little as 180 kg N ha^{-1} (Hochmuth, 1996). Assuming an (initial) linear response of fruit yield to N supply, this would translate to a slope (= nitrogen use efficiency, NUE) of roughly 0.5 t fruit [kg N]$^{-1}$. Under Florida conditions, experimental values for NUE ranged from 0.12 to 0.40, with values of approximately 0.35 being representative (Table 5-1). Bar-Yosef and Sagiv (1982), on the other hand, reported a NUE value of 0.07, which appears to be quite low relative to the values reported here. The use of irrigation and of greater plant densities appears to increase NUE values (Doss et al., 1975; Nassar, 1986). However, excessive water supply in combination with high

initial N rates may increase N leaching, and thereby result in reduced NUE values (Hochmuth, 1990).

Effects of Nitrogen Fertilizer Rates on Plant Growth

Results of our N-fertilizer studies are presented in Tables 5-2 through 5-7. Node development rates did not appear to be affected by N-rates. This is in variance with findings by Thompson et al. (1976), who reported that severe N-stress reduced node development rates for cotton. Typically the growth response to added N was most pronounced between 0 and 100 kg N ha^{-1}, with similar findings being observed for solution experiments by Larouche et al. (1989). Effects of higher N-rates on plant growth often only became obvious towards the end of the growing season, when N depletion of the soil started to affect plant growth. Effects of N rates on plant growth were more pronounced on coarse-textured soils (Tables 5-2 through 5-5) compared to more fine-textured soils (Tables 5-6 and 5-7). Dry weight of stems, leaves, fruits, and total dry matter production were generally greatest at the highest fertilizer rates. However, differences with relatively lower fertilizer rates were often (statistically) non-significant. In a number of cases (Gainesville 1996, Puerto Rico 1994, and Quincy 1994), fruit dry weights were highest at the next-to-highest fertilizer rate.

Average fruit harvest indices were on the order of 0.66, 0.56, 0.71, and 0.50 for Bradenton, Gainesville, Puerto Rico, and Quincy, respectively. These values are similar to those reported for greenhouse tomato, which range from 0.65 to 0.72 (Challa and Heuvelink, 1993). Typically, harvest indices decreased slightly with increased fertilizer

Table 5-1. Overview of reported yield response by tomato to N fertilizer for a number of production regions.

Location	Soil texture	N-response curve		Nmax (kg N ha^{-1})	Ymax [1] (t ha^{-1})	Reference
Auburn, AL	sandy loam	high irrigation	$y = 72 + 0.32 x - 0.00081 x^2$	197	104	Doss et al., 1975
		interm. irrigation	$y = 73 + 0.36 x - 0.00120 x^2$	145	99	
		no irrigation	$y = 60 + 0.18 x - 0.00074 x^2$	120	70	
Bradenton, FL	fine sand	total yield	$y = 26 + 0.42 x - 0.00060 x^2$	350	100	Bradenton 1995 (this study)
		marketable yield	$y = 20 + 0.36 x - 0.00046 x^2$	391	91	
Gainesville, FL	fine sand	total yield	$y = 24 + 0.39 x - 0.00069 x^2$	281	79	Gainesville 1996 (this study)
		marketable yield	$y = 22 + 0.36 x - 0.00071 x^2$	253	68	
Immokalee, FL	fine sand	spring crop	$y = 39 + 0.12 x - 0.00018 x^2$	344	59	Everett, 1976
		fall crop	$y = 17 + 0.16 x - 0.00014 x^2$	575	63	
Quincy, FL	loamy sand	spring 1983	$y = 63 + 0.40 x - 0.00160 x^2$	125	88	Rhoads et al., 1988
		spring 1984	$y = 54 + 0.24 x - 0.00053 x^2$	226	81	
		spring 1996	$y = 25 + 0.27 x - 0.00049 x^2$	276	62	Rhoads et al., 1996
Skierniewice, Poland	sandy loam	irrigated	$y = 41 + 0.39 x - 0.00074 x^2$	262	92	Kaniszewski et al., 1987
		non-irrigated	$y = 35 + 0.25 x - 0.00058 x^2$	216	62	
Fayoum, Egypt		12000 plants ha^{-1}	$y = 8 + 0.56 x - 0.00186 x^2$	151	55	Nassar, 1986
		36000 plants ha^{-1}	$y = -5 + 0.98 x - 0.00310 x^2$	158	72	
Punjab, India		fresh fruit weight	$y = 10 + 0.115 x - 0.0002 x^2$	288	27	Kooner and Randhawa, 1990
		fruit dry weight	$y = 0.6 + 0.0051x - 0.000012 x^2$	205	1.1	
		dry matter content	$y = 5.3 - 0.054 x$	--	--	
Cauca, Columbia	sandy clay	total fruit weight	$y = 41 + 0.19 x - 0.00039 x^2$	243	64	Jaramillo et al., 1978

[1] Fresh fruit yield unless indicated otherwise

Table 5-2. Summarized growth measurements, Bradenton N-fertilizer trial, spring 1994.

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
N = 180 kg ha^{-1} *							
0	3.1 ± 0.1	0.002 ± 0.0		0.06 ± 0.0	0.09 ± 0.00		0.15 ± 0.01
16	7.8 ± 0.5	0.008 ± 0.0	0.1 ± 0.0	0.16 ± 0.0	0.30 ± 0.06		0.52 ± 0.11
30	13.5 ± 0.5	0.21 ± 0.04	1.1 ± 0.3	4.7 ± 1.6	7.7 ± 1.5		13.4 ± 3.3
44	17.0 ± 1.0	1.29 ± 0.06	5.1 ± 0.4	38.8 ± 1.4	40.4 ± 0.6		88.4 ± 3.5
58	16.0 ± 0.0	4.61 ± 0.65	7.7 ± 0.3	125 ± 18.0	116 ± 9.0	83.1 ± 11.8	333 ± 15.4
72	17.5 ± 0.5	4.67 ± 0.53	7.9 ± 1.5	147 ± 13.6	121 ± 15.4	305 ± 22.2	581 ± 52.6
86	16.0 ± 1.0	4.87 ± 0.02	9.2 ± 1.6	181 ± 15.3	156 ± 12.5	512 ± 85.4	858 ± 115
100	17.5 ± 2.5	4.13 ± 0.55	9.1 ± 2.1	136 ± 12.5	151 ± 15.2	704 ± 117	1063 ± 155
N=258 kg ha^{-1}							
0	3.1 ± 0.1	0.002 ± 0.0		0.06 ± 0.00	0.09 ± 0.00		0.15 ± 0.01
16	7.3 ± 0.5	0.009 ± 0.0	0.1 ± 0.01	0.19 ± 0.02	0.35 ± 0.03		0.61 ± 0.05
30	14.0 ± 0.0	0.22 ± 0.0	1.2 ± 0.02	5.2 ± 0.2	8.2 ± 0.13		14.6 ± 0.4
44	16.5 ± 1.5	1.17 ± 0.10	3.9 ± 0.2	40.7 ± 1.8	40.5 ± 3.3		92.3 ± 6.4
58	18.5 ± 0.5	3.18 ± 0.38	5.7 ± 1.5	99.0 ± 17.9	81.5 ± 14.2	70.6 ± 2.1	257 ± 35.6
72	14.5 ± 0.5	6.00 ± 0.52	9.8 ± 0.2	211 ± 8.0	172 ± 3.8	372 ± 45.0	764 ± 49.0
86	16.5 ± 0.5	4.19 ± 0.78	6.7 ± 0.3	137 ± 25.6	120 ± 17.6	507 ± 19.8	771 ± 63.2
100	17.0 ± 1.0	5.26 ± 0.41	10.4 ± 1.1	211 ± 7.6	158 ± 14.8	763 ± 127	1142 ± 150
N=336 kg ha^{-1}							
0	3.1 ± 0.1	0.002 ± 0.0		0.06 ± 0.00	0.09 ± 0.00		0.15 ± 0.01
16	7.3 ± 0.6	0.010 ± 0.0	0.07 ± 0.01	0.16 ± 0.03	0.30 ± 0.06		0.52 ± 0.11
30	13.5 ± 0.5	0.25 ± 0.03	1.5 ± 0.3	6.0 ± 0.57	9.5 ± 0.98		16.9 ± 1.8
44	15.5 ± 0.5	1.56 ± 0.10	6.5 ± 0.2	53.4 ± 4.1	55.9 ± 3.1		120 ± 5.9
58	18.0 ± 0.0	4.27 ± 0.33	9.3 ± 0.0	141 ± 0.3	121 ± 2.9	112 ± 15.2	383 ± 12.6
72	16.0 ± 2.0	5.88 ± 0.48	9.4 ± 0.2	198 ± 20.6	173 ± 32.2	313 ± 67.3	694 ± 120
86	15.5 ± 0.5	5.05 ± 0.31	8.0 ± 0.2	178 ± 8.4	150 ± 3.3	478 ± 19.7	814 ± 31.1
100	16.0 ± 0.0	5.62 ± 0.97	11.1 ± 1.0	214 ± 40.1	159 ± 32.5	829 ± 12.6	1214 ± 84.3

* Values are averages of 2 replicates

Table 5-3. Summarized growth measurements, Bradenton N-fertilizer trial, spring 1995.

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
N = 0 kg ha^{-1} *							
0	4.3 ± 0.2	0.003 ± 0.0	0.07 ± 0.00	0.06 ± 0.00	0.09 ± 0.00		0.21 ± 0.01
14	10.7 ± 0.3	0.019 ± 0.0	0.07 ± 0.01	0.29 ± 0.01	0.70 ± 0.05		1.1 ± 0.05
26	15.3 ± 0.3	0.14 ± 0.01		3.0 ± 0.07	4.7 ± 0.47		7.6 ± 0.5
46	17.7 ± 0.6	0.76 ± 0.12		29.9 ± 2.3	28.8 ± 1.5	2.9 ± 1.3	61.7 ± 4.8
60	18.0 ± 1.7	0.82 ± 0.04		48.2 ± 0.5	30.9 ± 0.3	48.0 ± 3.7	133 ± 3.1
74	19.0 ± 1.0	0.53 ± 0.01		40.3 ± 2.5	22.1 ± 1.5	94.9 ± 5.5	165 ± 9.1
88	18.3 ± 0.3	0.33 ± 0.05		42.6 ± 2.9	16.8 ± 2.3	134 ± 20	209 ± 23.6
102	18.0 ± 0.6	0.10 ± 0.03		30.5 ± 3.7	6.5 ± 1.9	118 ± 5.6	172 ± 8.2
N = 100 kg ha^{-1}							
0	4.3 ± 0.2	0.003 ± 0.0	0.07 ± 0.00	0.06 ± 0.00	0.09 ± 0.00		0.21 ± 0.01
14	10.0 ± 0.0	0.019 ± 0.0	0.11 ± 0.02	0.25 ± 0.02	0.72 ± 0.06		1.1 ± 0.08
26	14.3 ± 0.3	0.15 ± 0.01		2.8 ± 0.27	4.8 ± 0.30		7.6 ± 0.5
46	18.7 ± 1.2	1.66 ± 0.15		48.0 ± 1.1	45.1 ± 3.1	2.1 ± 0.2	95.3 ± 4.2
60	17.7 ± 1.7	2.48 ± 0.24		76.7 ± 3.4	71.0 ± 4.6	102 ± 8.9	258 ± 5.7
74	22.3 ± 2.6	2.39 ± 0.12		110 ± 12.9	82.1 ± 7.5	281 ± 19.1	491 ± 37.8
88	18.7 ± 0.3	1.75 ± 0.34		117 ± 15.6	61.6 ± 8.9	338 ± 54.4	557 ± 77.3
102	17.3 ± 1.5	0.32 ± 0.12		90.2 ± 14.3	16.8 ± 6.1	377 ± 59.0	550 ± 72.6
N = 200 kg ha^{-1}							
0	4.3 ± 0.2	0.003 ± 0.0	0.07 ± 0.00	0.06 ± 0.00	0.09 ± 0.00		0.21 ± 0.01
14	10.7 ± 0.3	0.020 ± 0.0	0.11 ± 0.02	0.26 ± 0.02	0.70 ± 0.05		1.1 ± 0.10
26	15.0 ± 0.0	0.15 ± 0.01		3.1 ± 0.07	4.8 ± 0.62		8.0 ± 0.7
46	17.7 ± 0.6	1.83 ± 0.34		55.2 ± 6.4	48.7 ± 4.5	4.3 ± 1.8	108 ± 9.8
60	18.0 ± 0.5	3.19 ± 0.35		102 ± 4.8	79.3 ± 4.5	100 ± 3.1	288 ± 10.9
74	19.7 ± 1.9	3.15 ± 0.38		118 ± 15.3	86.7 ± 9.2	267 ± 26.0	486 ± 17.9
88	19.0 ± 1.5	2.28 ± 0.20		138 ± 7.9	82.3 ± 6.0	423 ± 25.5	679 ± 23.0
102	20.7 ± 1.0	0.57 ± 0.29		112 ± 25.3	23.9 ± 12.4	342 ± 27.5	553 ± 60.8
N = 300 kg ha^{-1}							
0	4.3 ± 0.2	0.003 ± 0.0	0.07 ± 0.00	0.06 ± 0.00	0.09 ± 0.00		0.21 ± 0.01
14	11.0 ± 0.0	0.019 ± 0.0	0.09 ± 0.01	0.38 ± 0.02	0.73 ± 0.07		1.1 ± 0.08
26	15.3 ± 0.3	0.14 ± 0.01		2.8 ± 0.18	4.7 ± 0.28		7.5 ± 0.4
46	19.3 ± 2.6	1.79 ± 0.32		53.3 ± 7.6	48.4 ± 4.6	5.5 ± 2.4	107 ± 9.8
60	19.0 ± 1.4	3.39 ± 0.16		96.5 ± 5.7	82.7 ± 6.4	104 ± 5.5	288 ± 11.3
74	21.7 ± 0.3	3.47 ± 0.17		113 ± 4.6	98.2 ± 3.6	272 ± 32.1	505 ± 41.3
88	17.0 ± 0.6	2.48 ± 0.05		143 ± 10.3	104 ± 1.7	429 ± 19.0	712 ± 33.5
102	19.7 ± 1.7	0.45 ± 0.16		117 ± 12.2	26.3 ± 9.5	446 ± 22.1	681 ± 36.6

* Values are averages of 3 replicates

Table 5-4. Summarized growth measurements, Gainesville N-fertilizer trial, spring 1995

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
N = 0 kg ha^{-1} *							
0	4.9 ± 0.2	0.003 ± 0.0	0.05 ± 0.0	0.08 ± 0.01	0.12 ± 0.01		0.25 ± 0.02
21	7.9 ± 0.5	0.04 ± 0.01	0.22 ± 0.0	0.68 ± 0.13	1.3 ± 0.3		2.12 ± 0.4
49	17.3 ± 0.3	0.19 ± 0.06		16.0 ± 3.4	12.0 ± 2.6	4.7 ± 2.1	32.7 ± 7.8
78	17.3 ± 0.7	0.19 ± 0.01	3.6 ± 0.2	22.3 ± 1.2	12.0 ± 0.3	39.1 ± 3.7	77.5 ± 4.9
94	19.0 ± 1.0	0.21 ± 0.07		25.5 ± 5.0	11.6 ± 3.4	49.5 ± 7.3	88.2 ± 13.7
N = 133 kg ha^{-1}							
0	4.9 ± 0.2	0.003 ± 0.0	0.05 ± 0.0	0.08 ± 0.01	0.12 ± 0.01		0.25 ± 0.02
21	12.3 ± 0.9	0.07 ± 0.01		1.5 ± 0.2	2.4 ± 0.4		3.7 ± 0.6
49	18.0 ± 0.0	0.72 ± 0.15		50.7 ± 7.4	26.4 ± 4.6	49.1 ± 2.9	126 ± 13.1
78	19.0 ± 0.6	0.85 ± 0.10	4.2 ± 0.6	73.9 ± 4.0	35.2 ± 2.2	116 ± 12.6	230 ± 12.0
94	16.7 ± 0.7	0.76 ± 0.04		86.1 ± 7.7	37.2 ± 2.1	212 ± 17.2	344 ± 28.9
N = 200 kg ha^{-1}							
0	4.9 ± 0.2	0.003 ± 0.0	0.05 ± 0.0	0.08 ± 0.01	0.12 ± 0.01		0.25 ± 0.02
21	12.0 ± 0.6	0.08 ± 0.01	0.38 ± 0.1	1.6 ± 0.1	2.7 ± 0.1		4.6 ± 0.1
49	17.7 ± 0.3	1.25 ± 0.23		57.9 ±10.2	41.8 ± 7.1	39.3 ± 4.8	138 ± 22.1
78	16.3 ± 1.3	0.97 ± 0.12		73.8 ± 4.2	41.6 ± 6.0	126 ± 3.7	242 ± 9.5
94	18.0 ± 0.6	0.65 ± 0.27		87.0 ± 7.7	27.7 ± 10.9	148 ± 13.2	280 ± 23.6
N = 266 kg ha^{-1}							
0	4.9 ± 0.2	0.003 ± 0.0	0.05 ± 0.0	0.08 ± 0.01	0.12 ± 0.01		0.25 ± 0.02
21	13.0 ± 1.0	0.08 ± 0.01		1.6 ± 0.2	2.7 ± 0.4		4.3 ± 0.6
49	16.7 ± 0.9	1.36 ± 0.05		69.4 ± 2.5	48.8 ± 1.8	41.9 ± 5.1	160 ± 7.3
78	17.3 ± 1.2	1.52 ± 0.11	6.2 ± 1.1	109 ± 13.0	71.3 ± 2.9	176 ± 11.6	363 ± 24.3
94	18.7 ± 1.2	1.02 ± 0.13		106 ± 3.7	49.3 ± 4.4	232 ± 31.6	396 ± 39.3
N = 333 kg ha^{-1}							
0	4.9 ± 0.2	0.003 ± 0.0	0.05 ± 0.0	0.08 ± 0.01	0.12 ± 0.01		0.25 ± 0.02
21	7.9 ± 0.5	0.08 ± 0.01	0.38 ± 0.1	1.6 ± 0.1	2.7 ± 0.1		4.6 ± 0.1
49	16.7 ± 0.7	1.42 ± 0.06		61.8 ± 6.4	47.4 ± 3.4	45.3 ± 2.8	154 ± 11.1
78	17.7 ± 2.0	1.60 ± 0.30	5.0 ± 1.3	107 ±15.8	67.3 ±13.4	143 ± 2.5	324 ± 30.1
94	16.3 ± 1.3	1.29 ± 0.20		119 ±11.5	55.9 ± 5.4	246 ± 31.1	430 ± 50.9

* Values are averages of 3 replicates

Table 5-5. Summarized growth measurements, Gainesville N-fertilizer trial, spring 1996

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
N = 0 kg ha^{-1} *							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
35	14.0 ± 0.4	0.06 ± 0.01		1.2 ± 0.23	2.0 ± 0.2		3.2 ± 0.3
56	18.5 ± 0.4	0.42 ± 0.05		27.3 ± 4.1	21.5 ± 2.3	2.6 ± 0.1	51.4 ± 6.3
77	18.0 ± 0.4	0.60 ± 0.21		47.1 ± 11.6	29.8 ± 7.7	71.3 ± 19.1	138 ± 38.1
91	18.0 ± 1.6	0.45 ± 0.07		44.3 ± 1.0	23.5 ± 1.9	101 ± 6.4	170 ± 3.3
N = 133 kg ha^{-1}							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
35	13.5 ± 0.4	0.11 ± 0.00		2.2 ± 0.12	3.8 ± 0.1		5.9 ± 0.3
56	18.0 ± 0.0	1.52 ± 0.01		74.9 ± 16.5	58.7 ± 6.1	11.6 ± 6.4	145 ± 16.1
77	17.0 ± 0.8	2.07 ± 0.14		104 ± 0.1	65.6 ± 0.7	241 ± 3.0	411 ± 2.1
91	20.5 ± 2.0	1.66 ± 0.08		122 ± 1.6	63.5 ± 3.5	269 ± 13.2	455 ± 15.5
N = 200 kg ha^{-1}							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
35	13.0 ± 0.0	0.14 ± 0.02		2.8 ± 0.23	4.7 ± 0.6		7.6 ± 1.7
56	19.0 ± 0.8	1.84 ± 0.29		85.4 ± 10.8	65.0 ± 5.4	12.3 ± 0.4	162 ± 16.5
77	19.0 ± 0.8	2.22 ± 0.04		125 ± 7.2	75.1 ± 1.5	217 ± 5.4	416 ± 3.1
91	20.0 ± 0.0	2.36 ± 0.07		134 ± 34.7	92.7 ± 9.9	253 ± 11.2	479 ± 18.7
N = 266 kg ha^{-1}							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
35	14.5 ± 0.4	0.16 ± 0.04		3.4 ± 1.00	5.4 ± 1.3		8.8 ± 2.3
56	18.0 ± 1.6	1.82 ± 0.13		95.6 ± 1.3	73.4 ± 6.6	6.9 ± 4.0	178 ± 1.2
77	18.5 ± 2.0	2.41 ± 0.19		127 ± 11.7	78.8 ± 3.7	221 ± 7.6	427 ± 22.4
91	20.0 ± 0.0	2.06 ± 0.06		156 ± 12.2	103 ± 22.3	303 ± 22.8	536 ± 34.3
N = 333 kg ha^{-1}							
0	5.1± 0.3	0.002	0.05	0.06	0.08		0.19
35	15.0 ± 0.0	0.18 ± 0.01		4.0 ± 0.13	6.3 ± 0.1		10.3 ± 0.2
56	19.5 ± 1.2	1.59 ± 0.07		68.9 ± 3.5	59.1 ± 1.7	15.2 ± 2.2	143 ± 0.3
77	20.5 ± 0.4	2.68 ± 0.30		115 ± 2.4	91.3 ± 8.8	248 ± 1.2	454 ± 9.9
91	21.0 ± 0.8	2.24 ± 0.41		155 ± 30.7	103 ± 22.3	286 ± 7.1	544 ± 59.9

* Values are averages of 3 replicates

Table 5-6. Summarized growth measurements, Puerto Rico N-fertilizer trial, 1994/1995.

DAP	LAI	Dry weight per plant (g)				
		Roots	Stems	Blades	Fruit	Total
N = 0 kg ha^{-1} *						
15	0.01 ± 0.0	0.10 ± 0.0	0.18 ± 0.3	0.60 ± 0.1		0.89 ± 0.15
29	0.20 ± 0.02	1.0 ± 0.1	1.6 ± 0.3	8.0 ± 1.0		10.6 ± 1.3
43	1.34 ± 0.13	3.5 ± 0.3	18.2 ± 1.5	53.7 ± 5.0	2.3 ± 0.6	77.7 ± 7.3
57	1.90 ± 0.39	4.7 ± 0.3	26.9 ± 3.9	70.1 ± 10	43.5 ± 8.2	145 ± 21.7
76	1.55 ± 0.14	4.2 ± 0.2	30.9 ± 2.5	76.0 ± 8.8	197 ± 52.9	308 ± 63.6
84	1.23 ± 0.14	3.9 ± 0.4	33.3 ± 3.6	70.2 ± 7.8	268 ± 13.6	376 ± 24.9
N = 75 kg ha^{-1}						
15	0.02 ± 0.0	0.14 ± 0.1	0.13 ± 0.1	0.62 ± 0.2		0.91 ± 0.30
29	0.18 ± 0.04	1.0 ± 0.2	1.7 ± 0.4	7.1 ± 1.4		9.8 ± 2.0
43	1.40 ± 0.18	3.0 ± 0.3	17.2 ± 2.3	49.0 ± 4.8	0.7 ± 0.3	69.9 ± 7.4
57	2.23 ± 0.24	4.8 ± 0.1	31.6 ± 1.1	82.0 ± 2.5	65.6 ± 3.8	184 ± 6.5
76	1.52 ± 0.19	5.4 ± 0.4	36.4 ± 1.9	85.1 ± 4.2	227 ± 30.2	353 ± 34.1
84	0.94 ± 0.05	3.4 ± 0.6	31.2 ± 1.4	65.1 ± 2.0	209 ± 25.4	309 ± 27.6
N = 150 kg ha^{-1}						
15	0.01 ± 0.0	0.07 ± 0.0	0.10 ± 0.0	0.46 ± 0.2		0.63 ± 0.17
29	0.24 ± 0.05	1.2 ± 0.2	2.0 ± 0.2	9.4 ± 1.8		12.6 ± 1.4
43	1.24 ± 0.15	3.2 ± 0.2	15.1 ± 1.4	45.9 ± 1.3	0.9 ± 0.4	65.1 ± 3.1
57	2.51 ± 0.30	5.7 ± 0.1	36.0 ± 3.2	89.6 ± 6.0	53.4 ± 6.0	185 ± 13.1
76	1.40 ± 0.11	5.1 ± 0.5	36.6 ± 2.1	79.0 ± 8.8	192 ± 30.9	313 ± 34.7
84	1.05 ± 0.23	4.5 ± 0.5	33.2 ± 3.6	73.8 ± 11	297 ± 60.8	408 ± 65.8
N = 225 kg ha^{-1}						
15	0.02 ± 0.0	0.08 ± 0.0	0.16 ± 0.0	0.75 ± 0.1		1.00 ± 0.10
29	0.24 ± 0.05	1.4 ± 0.2	2.2 ± 0.5	10.4 ± 2.3		13.9 ± 2.9
43	1.30 ± 0.09	3.3 ± 0.4	17.7 ± 1.5	52.2 ± 6.1	0.9 ± 0.3	73.9 ± 7.9
57	2.45 ± 0.19	5.3 ± 0.4	33.5 ± 0.8	85.3 ± 4.8	57.7 ± 5.2	182 ± 10.5
76	2.02 ± 0.17	5.5 ± 0.4	43.0 ± 2.6	106 ± 5.5	289 ± 45.6	443 ± 53.2
84	0.97 ± 0.09	4.5 ± 0.8	36.9 ± 3.8	76.8 ± 6.5	293 ± 38.2	411 ± 47.7

* Data obtained from F.H. Beinroth and recorded by M.A. Vazquez. Values are averages of 4 replicates

Table 5-7. Summarized growth measurements, Quincy N-fertilizer trial, fall 1995.

DAP	Node No.	LAI	Dry weight per plant (g) Roots	Stems	Blades	Fruit	Total
N= 0 kg ha^{-1} *							
0	6.3 ± 0.2	0.004 ± 0.0	0.14 ± 0.01	0.3 ± 0.01	0.2 ± 0.01		0.66 ± 0.03
23	13.7 ± 0.3	0.11 ± 0.02	0.54 ± 0.1	3.5 ± 0.9	5.0 ± 0.9		9.0 ± 1.9
43	17.7 ± 1.7	0.87 ± 0.15		42.8 ± 7.5	33.5 ± 5.0	0.0 ± 0.0	80.2 ± 12.3
63	18.7 ± 0.9	0.92 ± 0.22		67.9 ± 8.5	32.9 ± 6.9	36.5 ± 2.7	147 ± 18.2
84	18.7 ± 0.9	0.50 ± 0.15		57.3 ± 2.8	17.4 ± 3.7	95.4 ± 6.0	200 ± 15.3
N= 66 kg ha^{-1}							
0	6.3 ± 0.2	0.004 ± 0.0	0.14 ± 0.01	0.3 ± 0.01	0.2 ± 0.01		0.66 ± 0.03
23	13.3 ± 0.3	0.15 ± 0.01	0.43 ± 0.1	4.9 ± 0.6	6.6 ± 0.5		11.9 ± 1.1
43	18.3 ± 1.5	1.16 ± 0.08		47.0 ± 1.8	41.2 ± 3.8	0.0 ± 0.0	90.5 ± 4.8
63	18.0 ± 0.6	2.38 ± 0.67		100 ± 7.8	74.2 ± 18.7	42.3 ± 4.0	227 ± 29.8
84	17.3 ± 0.3	1.05 ± 0.15		81.5 ± 11.9	37.8 ± 7.2	175 ± 30.9	330 ± 61.0
N= 133 kg ha^{-1}							
0	6.3 ± 0.2	0.004 ± 0.0	0.14 ± 0.01	0.3 ± 0.01	0.2 ± 0.01		0.66 ± 0.03
23	14.3 ± 0.3	0.17 ± 0.01	0.64 ± 0.1	5.4 ± 0.3	7.1 ± 0.4		13.1 ± 0.5
43	17.7 ± 0.7	1.29 ± 0.06		50.2 ± 3.1	44.0 ± 3.3	0.5 ± 0.5	98.2 ± 7.6
63	17.3 ± 0.3	2.39 ± 0.22		120 ± 10.6	73.3 ± 6.8	60.6 ± 7.5	262 ± 15.2
84	18.7 ± 1.2	1.48 ± 0.13		109 ± 7.9	45.8 ± 4.0	185 ± 10.5	376 ± 23.5
N= 200 kg ha^{-1}							
0	6.3 ± 0.2	0.004 ± 0.0	0.14 ± 0.01	0.3 ± 0.01	0.2 ± 0.01		0.66 ± 0.03
23	14.3 ± 0.3	0.17 ± 0.03	0.70 ± 0.1	5.5 ± 0.9	7.6 ± 1.4		13.8 ± 2.3
43	17.3 ± 0.3	1.25 ± 0.12		54.6 ± 4.3	47.0 ± 5.0	1.0 ± 1.0	106 ± 10.8
63	17.7 ± 0.7	2.94 ± 0.26		137 ± 15.3	81.6 ± 5.7	44.7 ± 4.6	271 ± 14.7
84	18.7 ± 1.2	1.99 ± 0.30		124 ± 11.5	65.1 ± 6.7	272 ± 14.6	506 ± 37.8
N=266 kg ha^{-1}							
0	6.3 ± 0.2	0.004 ± 0.0	0.14 ± 0.01	0.3 ± 0.01	0.2 ± 0.01		0.66 ± 0.03
23	13.7 ± 0.3	0.15 ± 0.02	0.60 ± 0.1	4.5 ± 0.8	6.6 ± 1.0		11.8 ± 1.9
43	16.3 ± 0.7	1.63 ± 0.41		54.7 ± 11.8	46.5 ± 6.9	0.0 ± 0.0	104 ± 18.8
63	18.0 ± 0.6	2.66 ± 0.34		105 ± 7.4	75.4 ± 6.0	57.1 ± 9.7	247 ± 22.3
84	17.0 ± 1.6	2.36 ± 0.22		128 ± 11.5	66.0 ± 2.3	216 ± 5.7	449 ± 23.4

* Values are averages of 3 replicates

rates, but trends were not always consistent. Based on field observations, excessively high N rates favored vegetative development and delayed crop senescence. Similar results have been reported in the literature (Doss et al., 1975; Huett and Dettmann, 1988; Larouche et al., 1989). N-stress, on the other hand, shortened the fruiting period, favored fruit maturation, and resulted in a more rapid onset of crop senescence. Doss et al. (1975) reported that, with an increase in N rates from 65 to 260 kg N ha^{-1}, the percentage of senescent plants at the end of the growing season decreased from 55% to 5%.

Absolute growth rates for tomato increased from 0.007 g $plant^{-1}$ d^{-1} for transplants to a maximum rate of 11 to 25 g $plant^{-1}$ d^{-1} at 11 weeks after transplanting (Fig. 5-1). This translates to maximum dry matter accumulation rates of 120 to 280 kg ha^{-1} d^{-1}. Reported values in the literature include 12-14 g $plant^{-1}$ d^{-1} (200-250 kg ha^{-1} d^{-1}) for greenhouse tomato (Bertin and Gary, 1993; Cooper, 1972; Koning, 1993) and 200 kg ha^{-1} for other field crops (van Keulen, 1981). In the absence of N fertilizer, absolute growth rates were only 20-30% of maximum rates. Reductions in growth rate due to moderate N-stress, on the other hand, only became obvious toward the end of the growing season and were typically below 18% (Fig. 5-1).

The absolute growth rates presented here can be used to calculate optimal concentrations of N in the soil solution. Assuming a dry matter increase of 280 kg dry matter ha^{-1} d^{-1} and a plant tissue N-content of 0.032 kg N kg^{-1}, maximum daily N-uptake would be on the order of 9 kg N d^{-1} [Bar-Yosef and Sagiv (1982) reported a value of 8 kg N ha^{-1}]. Based on a maximum transpiration rate of 4.8 mm d^{-1}, and assuming that N uptake occurs mainly by mass flow, required N concentration in the soil solution should

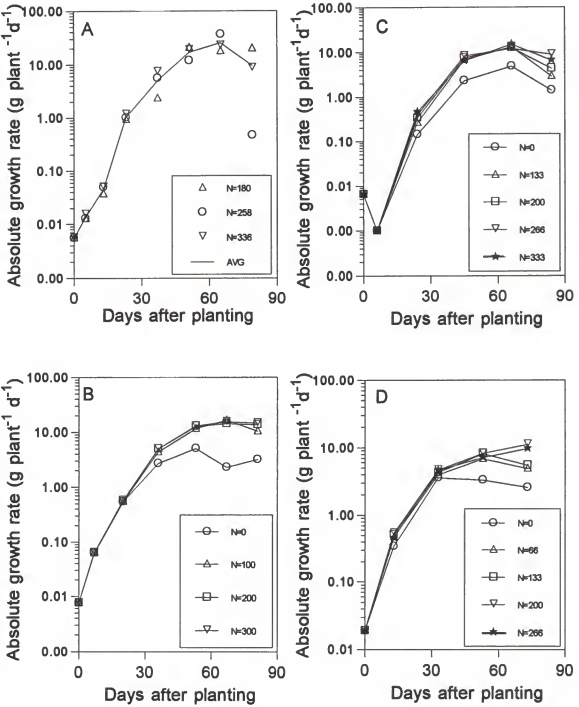


Fig. 5-1. Effect of N-fertilizer rate on the absolute growth rate of tomato for the a) Bradenton 1994 spring season; b) Bradenton 1995 spring season; c) Gaineville 1996 spring season; and Quincy 1995 fall season.

be on the order of 150 to 200 ppm N (10 to 15 meq NO_3-N L^{-1}) for optimal growth. These calculated values appear to be in agreement with results from both field experiments and solution culture, which have reported that maximum growth and N uptake by tomato occurs at solution concentrations of 150 to 200 ppm N (Bar-Yosef and Sagiv, 1982; Larouche et al., 1989). Huett and Dettman (1988) reported that maximum vegetative growth and highest early fruit yields occurred at 121 ppm N. However, total fruit yields were highest at solution-N concentrations of 450 ppm.

N-stress resulted in a decrease in partitioning of dry matter to stems and leaves and increased retranslocation of assimilates to fruits towards the end of the growing season (Fig. 5-2a to 5-2c). The effects of N-rates on dry matter partitioning were more pronounced for the coarse-textured soil at Bradenton (Fig. 5-2a to 5-2c) compared to the more fine-textured soil at Quincy (Fig. 5-2d to 5-2f). Negative values for stem and leaf partitioning coefficients, and fruit partitioning coefficients greater than unity for the zero-N treatment at Bradenton, may be related to retranslocation of assimilates to the fruit and leaf abscission. Increasing N-fertilizer rates, on the other hand, appeared to favor the partitioning of dry matter to vegetative growth. Based on such results, and on reports in the literature, it may be concluded that N-stress during initial growth may increase the partitioning of dry matter to the fruit (Nicola and Basoccu, 1994). High N-rates, on the other hand, may result in lower initial partitioning of assimilates to fruits. High rates also may increase the fruiting ("filling stage") duration for tomato plants, however, and thus result in an increase in total fruit yields (Huett and Dettmann, 1988; Thompson et al., 1976).

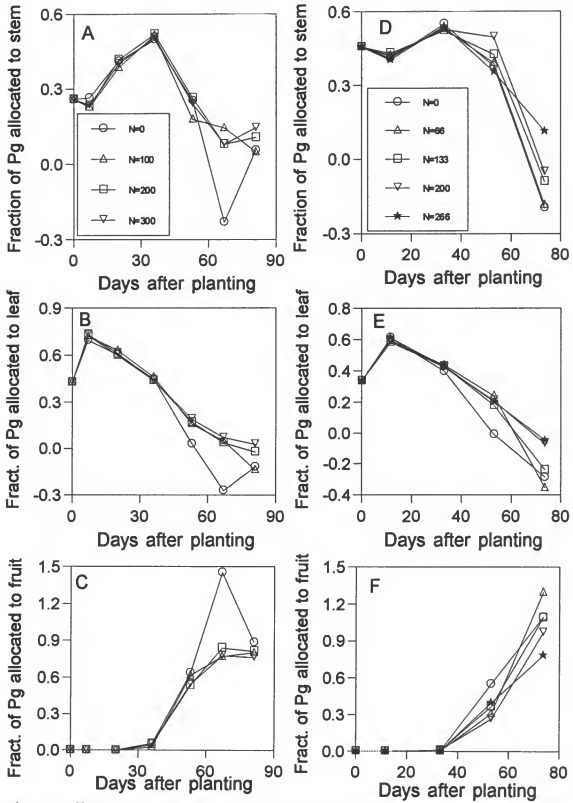


Fig. 5-2. Effects of N-fertilizer rate on partitioning of total photosynthates within the total assimilate fraction to a) stems; b) leaves; and c) fruit (for the Bradenton 1995 N-experiment). and to d) stems; e) leaves; and f) fruit (for the Quincy 1995 N-experiment).

Leaf area index (LAI) values were typically greatest at the higher N-rates, with maximum LAI values increasing from 0.6-1.0 to 2.5-3.5 as N-fertilizer rates increased to 300 kg N ha^{-1} (Fig. 5-3a to 5-3c). An increase in N-rate may also, in some cases, result in slightly later onset of canopy senescence (Fig. 5-3a). The increase in LAI with increasing N-rates may be caused by an increase in leaf number (Fig. 5-3d to 5-3f), an increase in average leaf size (Fig. 5-4a to 5-4c), and/or an increase in specific leaf area (Fig. 5-4d to 5-4f). The most drastic changes in these leaf characteristics typically occurred between N rates of 0 and 100 kg N ha^{-1}. N-stressed plants typically had fewer leaves and leaves were both smaller and thicker (smaller SLA values). With a further increase in N supply, additional increases in leaf numbers were more pronounced compared to respective increases in leaf size or SLA values. Similar results were reported for young tomato plants by Nicola and Basoccu (1994) and Masson et al. (1990).

An overview of the effects of N-rates on photosynthetic measurements for Gainesville (1995 and 1996) and Quincy (1995) is presented in Table 5-8. In order to account for the effects of N concentration and leaf thickness on photosynthesis, results are also plotted against leaf N concentrations and specific leaf N values (Fig. 5-5). The relative photosynthetic rates (Pg/Pgmax) shown in Fig. 5-6 were introduced in order to combine results for the different locations and growing seasons. The data envelope shown in Fig. 5-6 was included to show potential photosynthetic rates for specific N-levels. The relatively low photosynthetic rates during the 1995 growing season (Table 5-4) may have been related to water stress due to clogging of the irrigation system, three weeks prior to the measurements. Stomatal conductance and leaf-N content at the time of the

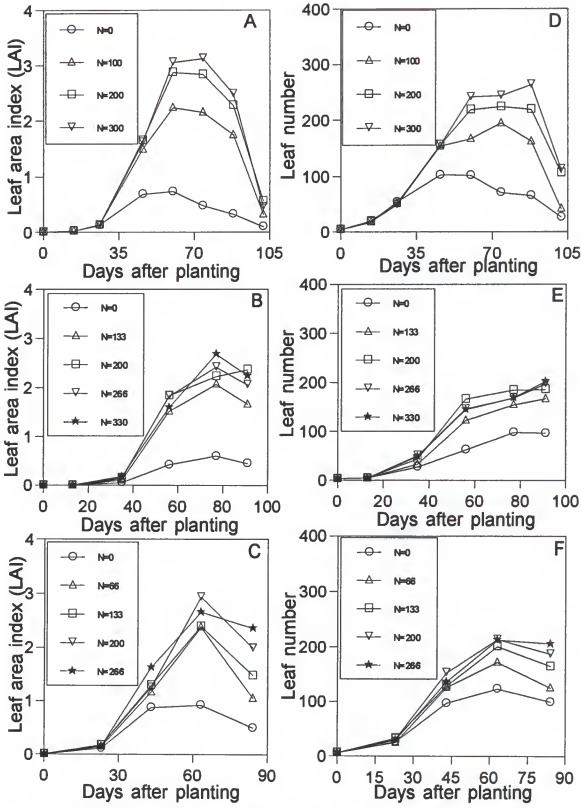


Fig. 5-3. Effect of N-fertilizer rate on (a-c) leaf area index; and (d-f) leaf number for Bradenton 1995 (a and d); Gainesville 1996 (b and e); and Quincy 1995 (c and f).

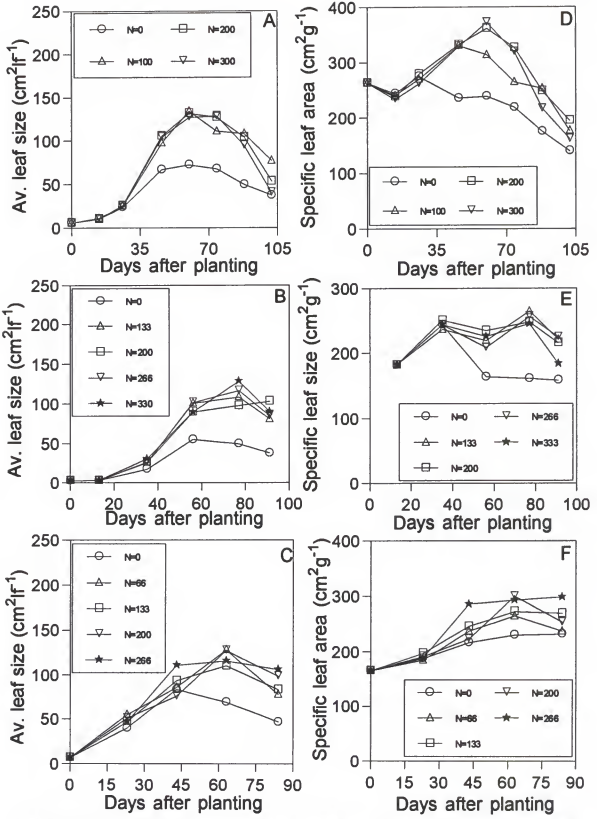


Fig. 5-4. Effect of N-fertilizer rate on (a-c) average leaf size and (d-f) specific leaf area for Bradenton 1995 (a and d); Gainesville 1996 (b and e); and Quincy 1995 (c and f).

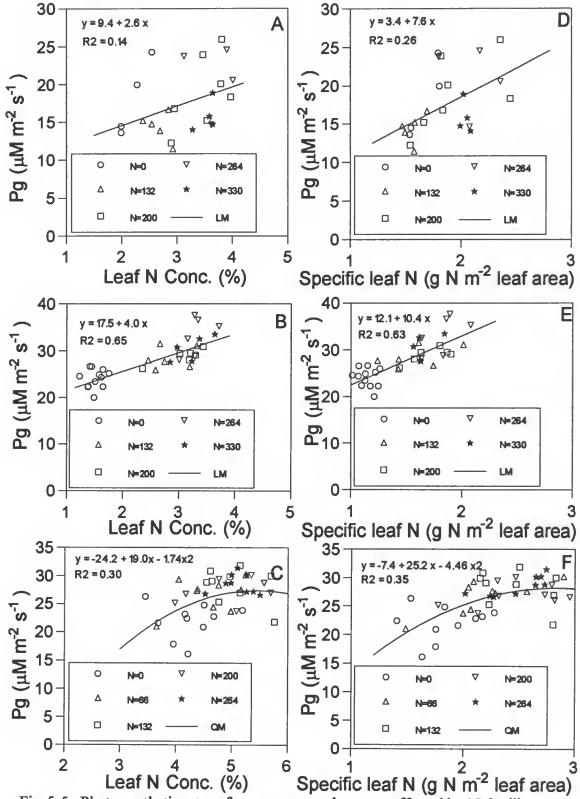


Fig. 5-5. Photosynthetic rates of mature tomato leaves as affected by N-fertilizer rates and plotted against either (a-c) leaf N concentration; or specific leaf N (d-f); for Gainesville 1995 (a and d); Gainesville 1996 (b and e); and Quincy 1995 (c and f).

Table 5-8. Overview of the effects of N rates on leaf N concentration , specific leaf N (SLN), specific leaf area (SLA), dry matter percentage (DMP), stomatal conductance (Cs), and leaf photosynthesis (Pg) for Gainesville 1995 and 1996; and Quincy 1995.

N-rate ($kg\ ha^{-1}$)	% N	SLN ($g\ N\ m^2$ leaf area)	SLA ($cm^2\ g^{-1}$)	DMP	Cs ($cm\ s^{-1}$)	Pg ($\mu Mol\ m^{-2}\ s^{-1}$)
Gainesville 1995						
N= 0	2.21 ± 0.13	1.68 ± 0.07	131.7 ± 3.5	21.3 ± 0.6	3.21 ± 0.63	17.9 ± 2.5
N= 133	2.69 ± 0.10	1.57 ± 0.04	171.4 ± 6.0	22.1 ± 0.8	2.12 ± 0.31	14.2 ± 0.9
N= 200	3.50 ± 0.16	1.94 ± 0.13	182.5 ± 7.9	20.6 ± 1.0	2.66 ± 0.32	18.8 ± 1.8
N= 266	3.67 ± 0.19	2.10 ± 0.10	174.6 ± 1.5	21.2 ± 0.8	2.26 ± 0.61	20.7 ± 2.8
N= 333	3.54 ± 0.09	2.04 ± 0.02	173.7 ± 5.8	20.9 ± 0.7	2.05 ± 0.21	15.7 ± 1.1
Gainesville 1996						
N= 0	1.52 ± 0.04	1.15 ± 0.02	131.8 ± 2.9	24.6 ± 0.4	1.53 ± 0.15	23.8 ± 0.6
N= 133	2.84 ± 0.14	1.58 ± 0.11	181.3 ± 8.6	20.9 ± 0.3	1.66 ± 0.09	28.2 ± 0.9
N= 200	3.09 ± 0.16	1.70 ± 0.07	181.4 ± 5.8	21.0 ± 0.4	1.54 ± 0.06	28.6 ± 0.6
N= 266	3.31 ± 0.10	1.82 ± 0.07	181.6 ± 2.7	19.8 ± 0.3	1.83 ± 0.10	32.8 ± 1.6
N= 333	3.22 ± 0.14	1.66 ± 0.07	193.5 ± 5.8	20.6 ± 0.4	1.68 ± 0.12	30.2 ± 1.2
Quincy 1995						
N= 0	4.26 ± 0.16	1.85 ± 0.09	234.0 ± 10	17.8 ± 0.9	2.05 ± 0.07	21.8 ± 1.0
N= 66	4.59 ± 0.18	2.19 ± 0.13	212.4 ± 8.6	18.1 ± 0.3	2.50 ± 0.08	26.3 ± 1.0
N= 133	5.04 ± 0.15	2.47 ± 0.10	205.2 ± 4.9	18.0 ± 0.5	2.48 ± 0.07	28.1 ± 1.1
N= 200	5.25 ± 0.28	2.48 ± 0.13	212.2 ± 5.9	17.5 ± 0.5	2.54 ± 0.12	26.8 ± 0.7
N= 266	5.10 ± 0.10	2.50 ± 0.09	206.8 ± 9.8	17.7 ± 0.2	2.69 ± 0.15	28.4 ± 0.6

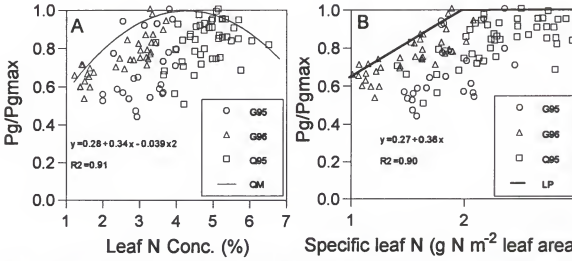


Fig. 5-6. Relative photosynthetic rates (Pg/Pgmax) of tomato leaves plotted against a) leaf N concentrations; and b) specific leaf N; the quadratic model expresses relative Pg (x) as a function of N concentraion (y); the linear plateau expresses relative Pg (x) as a function o f specific leaf N (y).

measurements, on the other hand, appeared to be relatively high compared to the 1996 growing season. It may be possible that the overall photosynthetic capacity of leaves was relatively low due to prior water stress. It could be hypothesized that the relatively small plants in the zero N-treatment were not as severely affected by water stress due to their relatively low rates of water consumption. Higher stomatal conductance observed with this treatment seems to provide some support for this theory. In most cases there was a fair amount of "scattering" in both N-content, specific N, and photosynthetic rates for the various N treatments (Fig. 5-5). Some of this variation may be associated with differences in leaf age, since both photosynthetic rate and leaf N-content of tomato decrease as leaves age (Tanaka et al., 1974).

Even though leaf N concentrations for the zero-N treatment at Gainesville in 1996 could be considered deficient (< 2.5 %; Hochmuth et al., 1991), overall photosynthesis was still 73% of the maximum observed rate. These results are in contrast with reports for peanut, where photosynthetic rates under similar N-stress conditions were only 27% of the maximum observed rate (Sinclair et al., 1993). Motta and Medina (1978), using N-depleted solutions to induce severe N-stress in young tomato plants, reported resulting N-tissue levels on the order of 1.3% N, with observed photosynthetic rates only approximately 60% of the maximum observed rates.

Plant growth for the zero N-rate at Quincy was relatively vigorous compared to that observed for Gainesville. Leaves also appeared to be relatively larger, thinner, and greener compared to those for Gainesville. It appears that N-stress at Quincy was thus relatively mild, especially since most of the measured leaves tested "adequate" for N.

It may be concluded that leaf photosynthesis for tomato is less sensitive to N-stress than is peanut. Based on results presented in Fig. 5-6, maximum photosynthetic rates for tomato leaves are attained at tissue concentrations of 3.8% and specific leaf N-values of about 2.0. Respective values for peanut, on the other hand, are 5.0 to 5.5% and 3.0 (Sinclair et al., 1993). A slope of 0.36 (Fig. 5-6) for the relative photosynthetic values plotted against specific leaf N (Fig 5-6b) is slightly lower than the value (0.4) calculated for the data presented by Sinclair. It appears that severe N-stress in tomato results in the formation of smaller and fewer leaves. Apparently, however, the overall photosynthetic capacity per leaf unit is not reduced as much nor as readily as is the case for non-nodulated peanut. These results could be used for modeling purposes. Overall photosynthetic rates reported here are slightly higher than the values reported for greenhouse tomato but slightly lower than those for peanut (Jones et al., 1989b; Sinclair et al., 1993).

Effects of N-rates on radiation use efficiency (RUE) values are shown in Fig. 5-7. Observed values for peanut were 0.76 g MJ^{-1} (Bennett et al., 1993), which is lower than the value of 0.81 observed at Quincy but higher than all other calculated values. The reduction in RUE values due to N-stress shown in Fig 5-7 is due to a reduction in both light interception and photosynthetic rates. The fraction of light absorbed as a function of LAI can be calculated as follows:

$$RAD_{abs} = (1 - e^{-k * LAI}) \qquad (1)$$

where RAD_{abs} = the fraction of light absorbed by the canopy and k = light extinction

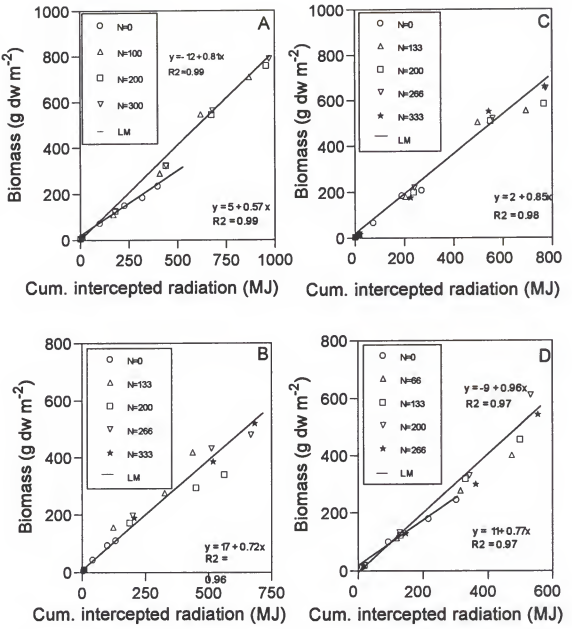


Fig. 5-7. Tomato dry weight accumulation of above-ground biomass plotted as a function of cumulative intercepted radiation for different N-fertilizer treatments for the a) Bradenton 1995 spring season; b) Gainesville 1995 spring season; c) Gainesville 1996 spring season; and d) Quincy 1995 fall season; linear models express biomass dry weight (y) as a function of cumulative intercepted radiation.

coefficient, for which a value of 0.60 was assumed. Based on this equation light interception values of 0.25, 0.50, 0.75, and 0.9 would correspond with LAI values of 0.5, 1.25, 2.5, and 4.5, respectively. Although severe N stress reduced light interception and biomass accumulation appreciably, its effect on RUE values was small and in most cases reductions in RUE were well below 20-30%. This reduction in RUE is most likely related to a reduction in photosynthesis. No obvious differences in RUE were discerned between higher N-rates. It may thus be concluded that reduced light interception was the prime cause for yield reduction due to N-stress, whereas the reduction in photosynthesis appears to be of smaller importance. The implication of these results on production agriculture is that a reduction in recommended N-rates may also require a revision of the recommended plant spacings in order to minimize yield reductions due to incomplete light interception.

Effects of Nitrogen Supply on Nitrogen Uptake

Tissue nitrogen concentration

Tissue N concentrations for tomato tissue from Bradenton 1991, 1992, 1994, and 1995; Gainesville 1996; Immokalee 1995; and Quincy 1995 are shown in Figs. 5-8 to 5-11. Initial N concentrations were typically relatively low (Figs. 5-8c; 5-9a to c; 5-10a to d; and 5-11a to c). This could have been related to transplant handling or to cold weather during initial growth. Transplants are commonly produced in "Speedling" trays, and nutrients are readily leached from the associated small root volumes. If transplants are stored before transplanting occurs, and no additional fertilizer is added to the irrigation

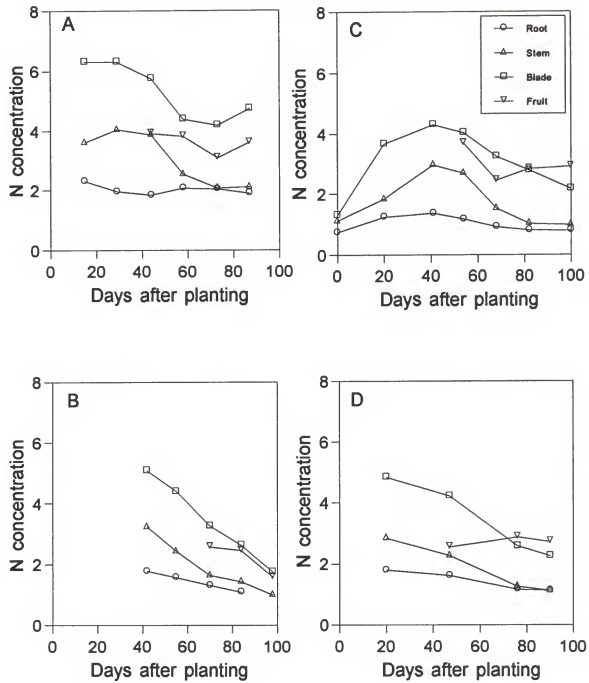


Fig. 5-8. The N concentrations of root, stem, leaf, and fruit tissue for tomato plants grown at a) Bradenton 1991; b) Bradenton 1992; c) Immokalee 1995; and d) Quincy 1995;

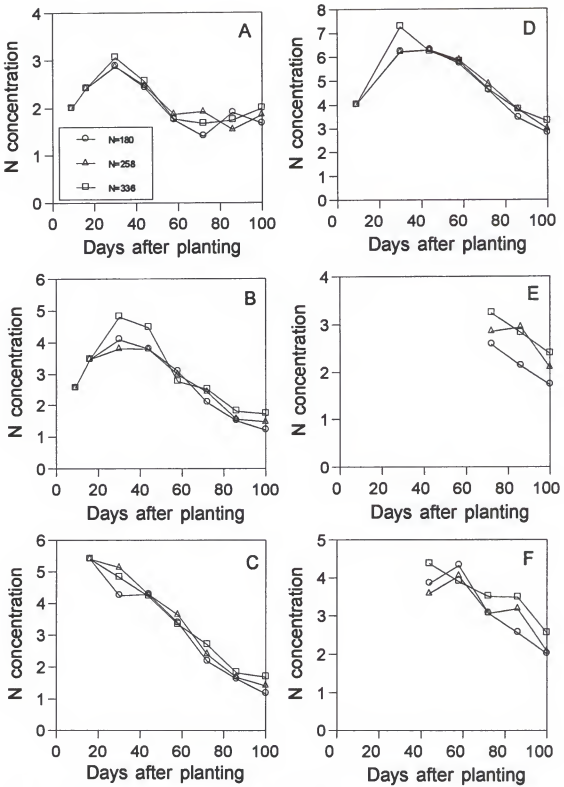


Fig. 5-9. Effects of N-fertilizer rates on N concentrations of a) root; b) stem; c) petiole; d) leaf blade; e) senescent leaf; and f) fruit for tomato grown during the 1994 spring season at Bradenton.

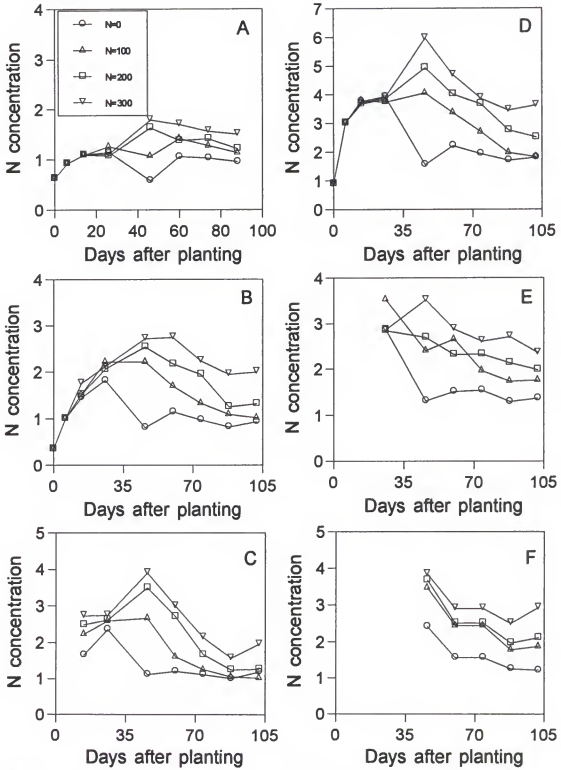


Fig. 5-10. Effects of N-fertilizer rates on N concentration of a) root; b) stem; c) petiole; d) leaf blade; e) senescent leaf; and f) fruit for tomato grown during the 1995 spring season at Bradenton.

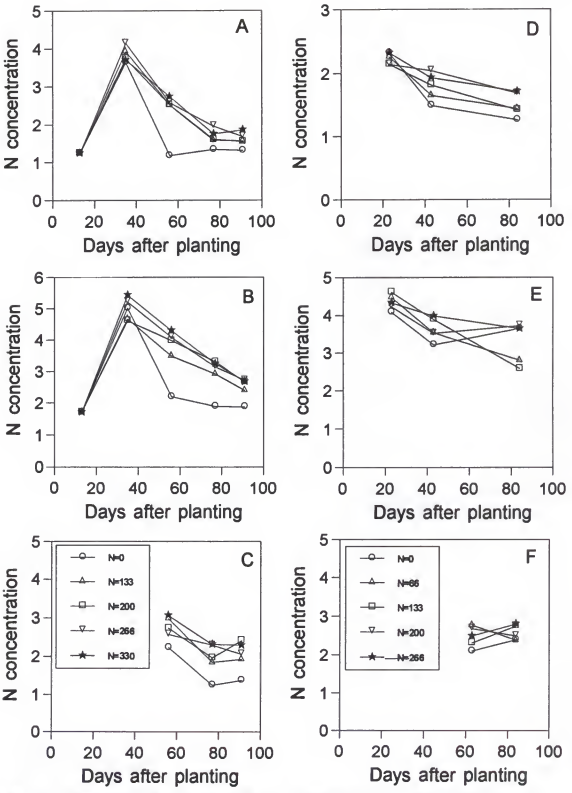


Fig. 5-11. Effects of N-fertilizer rates on N concentration of a) stem; b) leaf; and c) fruit for the 1996 spring season in Gainesville; and of d) stem; e) leaf; and f) fruit for the 1995 fall season at Quincy.

water, N depletion of the tissue may occur. If cold temperatures also prevail after transplanting, root growth and plant evaporation may be relatively low, resulting in a further delay in N uptake. Applying additional N prior to transplanting may thus be desirable, since it has been reported to increase early fruit yield (Melton and Dufault, 1991; Nicola and Basoccu, 1994)

Typically, N concentrations were highest in leaf blades; intermediate for stems, petioles, and fruits; and lowest for roots and senescent leaves. The N content of leaf blades decreased from 5-8% N (2-4 weeks after transplanting) to 2-3% near the end of the growing season. In most cases, N concentrations of stem and petioles were similar, decreasing from 4-6% during initial growth to 1-3% at harvest. Respective values for fruits were on the order of 3-4% and 2-3%.

With subirrigation all fertilizer was applied before transplanting. This resulted in relatively high N concentrations early in the season, followed by a linear decrease in N concentration of the tissue over time (Figs. 5-8b and 5-9d). This decrease in tissue N concentration was less obvious during the 1992 and 1995 seasons (Figs. 5-8a and 5-10), which may have been related to lower growth rates and/or amounts of biomass accumulation for these years. As a result, the dilution of N in the plant tissue during the rapid growth phase may have been less pronounced, resulting in higher N concentrations during the latter part of the growing season. The linear decrease in N concentration of leaves over time is most likely caused by N dilution due to leaf aging and possible N retranslocation to fruits under N-limiting conditions. Similar trends have been observed in field studies with tomato and cotton (Huett and Rose, 1988; Thompson et al., 1976).

With the use of drip irrigation typically only 20-40% of the fertilizer was applied preplant, with the remainder being applied with the irrigation water. As a result, initial N values were lower and the decrease in tissue N concentrations over time was less pronounced (Figs. 5-9d and 5-11).

N-stress affected N concentrations of leaves and stems most drastically, whereas concentrations in fruits and roots were affected to a lesser extent. Initial differences between fertilizer treatments for Gainesville and Bradenton (Figs.5-10 and 5-11a to c) were relatively small, but became more pronounced as the plants entered the rapid growth phase. Similar results have been reported for cotton (Thompson et al., 1976). Differences between N treatments were less pronounced at Quincy (Figs. 5-11d to f), which may have been related to higher residual N contents and to the relatively high moisture- and nutrient-retention-capacities of this soil. For subirrigated crops, leaf tissue tested "high" until initial flowering, and "adequate" throughout the rest of the growing season. However, the zero-N treatment (Fig. 5-10d) tested deficient after initial flowering. During 1992 and 1994, and with the lowest N-rate (N=100 kg ha^{-1}) during 1995, N concentrations approached the "deficient" range near the end of the growing season (Hochmuth et al., 1991). Except for the zero-N treatment at Gainesville during the 1996 growing season, all drip-irrigated treatments tested "adequate" during the entire growing season (Fig. 5-8c to d; and 5-11b and e). The increase in leaf tissue concentration with an increase in N-rate is in agreement with other N-rate studies (Csizinszky et al., 1988; Wien and Minotti, 1987). Excessively high N levels for subirrigated crops, on the other hand, could have resulted in N accumulation in both stems and fruits (Figs. 5-10c and f).

However, luxury consumption of N may not necessarily result in additional yield increases (Hochmuth et al., 1989). In some cases, it may even result in reductions of marketable fruit yields (Wien and Minotti, 1987).

Nitrogen accumulation by tomato plants

The accumulation of N in tomato plants is of importance if we are to make inferences with respect to total N uptake over time, and concerning the proportion of N recovery by the crop. Total N accumulation by tomato for a number of growth studies and N rates is shown in Fig. 5-12. It may be concluded that N uptake during the first month after transplanting comprises less than 10% of the seasonal N uptake. Total N accumulation depended on crop yield and nutrient supply, and ranged from 15 to 50 kg N ha^{-1} for severely N-stressed plants to 140 to 240 kg N ha^{-1} under non-limiting conditions (Table 5-8). However, unfavorable growing conditions (Gainesville, 1995) may limit N accumulation to values around 90 kg N ha^{-1} and may also reduce fertilizer recovery, thereby decreasing fertilizer-use efficiency. Apparent N recovery can be defined as:

$$ANR = \frac{(U_F - U_0)}{N_F} \qquad (2)$$

where ANR is apparent N recovery; U_F and U_o are N uptake by the crop in the presence and absence of fertilizer N; and N_F is the amount of fertilizer applied (Greenwood and Draycott, 1988). Calculated ANR values for subirrigated tomato were two-fold higher than those for drip-irrigated crops, and values typically decreased with an increase in N rate (Table 5-9). Lower ANR values for drip-irrigated crops are most likely related to the

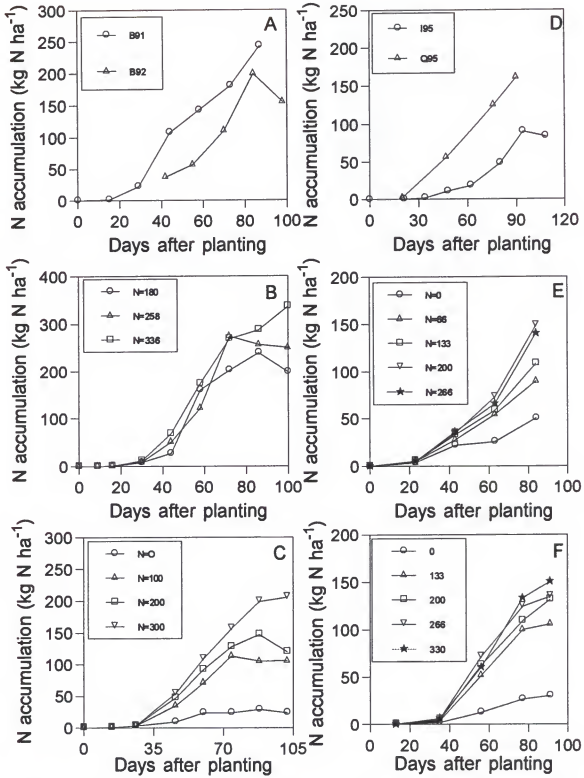


Fig. 5-12. Accumulation of N by tomato plants for a) Bradenton1991 and 1992; b) Bradenton 1994; c) Bradenton 1995; d) Immokalee and Quincy 1995; e) Quincy 1995 (fall); and f) Gainesville 1996;

Table 5-9. Calculated N accumulation by the tomato crop, and fertilizer recovery rates, for Bradenton 1991, 1992, 1994 and 1995; Gainesville 1995 and 1996; Immokalee 1995; and Quincy 1995

Location	N-rate ($kg\ ha^{-1}$)	N-accumulation ($kg\ N\ ha^{-1}$)	ANR
Bradenton 1991	230	243	0.96 [1]
Bradenton 1992	180	199	0.98 [1]
Bradenton 1994	180	198	0.98 [1]
	258	249	0.88 [1]
	336	336	0.91 [1]
Bradenton 1995	0	23	--
	100	106	0.82
	200	120	0.48
	300	206	0.61
Bradenton 1995 (F)	200	207	0.92 [1]
Gainesville 1995	0	16	--
	133	71	0.41
	200	60	0.22
	266	90	0.28
	333	96	0.24
Hochmuth 1995	195	167	0.77
Gainesville 1996	0	30	--
	133	125	0.71
	200	123	0.46
	266	140	0.41
	333	150	0.36
Immokalee 1995	260	90	0.26 [1]
Immokalee 1995 (F)	220	141	0.54 [1]
Quincy 1995	202	161	0.55 [2]
Quincy (F)	0	50	--
	66	89	0.74
	133	108	0.44
	200	149	0.50
	266	140	0.34

[1] Estimated assuming a value for U_e of 23 $kg\ N\ ha^{-1}$, based on the results for the 1995 growing season at Bradenton

[2] Estimated assuming a value of U_e of 50 $kg\ N\ ha^{-1}$. based on the results for the 1995 growing season at Quincy

N leaching typically observed with drip irrigation. Higher ANR values for subirrigated crops may be related to the predominant upward movement of water and solutes with this irrigation method.

Samples taken from the surficial groundwater at a soil depth of 60 cm during the 1995 growing season at Bradenton showed consistently low N values (< 1 ppm) even at the highest N rates. The decrease in ANR values with an increase in N rates is in agreement with reports in the literature. Reported ANR values for cabbage using the above approach were 0.78 and 0.59 at N rates of 150 and 300 kg ha^{-1} (Greenwood and Draycott, 1988). Reported cumulative N uptake and REC values for a study using labeled N with drip-irrigated tomato fertilized at an N rate of 220 kg ha^{-1} were 145 kg ha^{-1} and 0.40, respectively (Sweeney et al., 1987). These values compare favorably to those observed at Gainesville during the 1996 growing season. Total N accumulation in tomato plants grown on a loamy soil in California increased from 240 to 400 kg ha^{-1} as N rates increased from 160 to 585 kg N ha^{-1} (Stark et al., 1983). Based on results presented in Table 5-9 and reports in the literature, 25-60% of the plant N may come from soil N for fine-textured soils and soils with relatively high (> 3%) organic matter contents (Miller et al., 1981; Sweeney et al., 1987). Sweeney et al. (1987) reported that, under Florida conditions, steady-state soil N levels were on the order of 1-2 ppm, and that 2-4% of the organic-N can becomes available for plant uptake during the growing season. Based on these results, N supply from mineralization may be on the order of 10-40 kg N ha^{-1} during the growing season for soils with an organic matter content of 1-2%, which is in agreement with the results shown in Table 5-9.

Effects of Nitrogen Supply on Nitrogen Distribution

Approximately 60 to 70 % of the total N taken up during initial growth is accumulated in the leaves (Fig. 5-13) compared to roughly 20-40% in stems. During fruit development, approximately 30 to 50% and 20 to 30% of the total N uptake was stored in leaves and stems, respectively. These percentages decreased to approximately 20 to 25% and 15 to 20%, respectively, near the end of the growing season. Accumulation of N by the roots decreased from 15 to 25% during initial growth to around 1 to 2% near the end of the growing season. N-stress resulted in a relatively higher fraction of N being accumulated in the fruit and in a reduction in N accumulation by vegetative plant parts (Fig. 5-13c and d). With adequate N supply, N accumulation in the fruit at the end of the season ranged from 50 to 70%. However, under severe N stress, this value increased to roughly 75%. Reported values in the literature ranged from 40 to 70% (Bar-Yosef et al., 1980; Stark et al., 1983; Sweeney et al., 1987), while Stark et al. (1983) reported that, for an increase in N rates from 120 to 585 kg ha^{-1}, N accumulation by the fruit decreased from 50 to 40%.

Tomato seeds and fruit pulp contained 90.1 and 9.9% of total fruit N, respectively. Under severe N-stress, N concentration of seeds decreased from 5.1% to 4.4% N, with respective values for the fruit pulp of 2.5 and 1.7% N. Severe N-stress also resulted in increased N accumulation by the seeds, to approximately 12%.

The effects of N rates on N-partitioning coefficients for tomato are shown in Fig. 5-14. Severe N stress resulted in a decreased partitioning of N to both leaves and stems

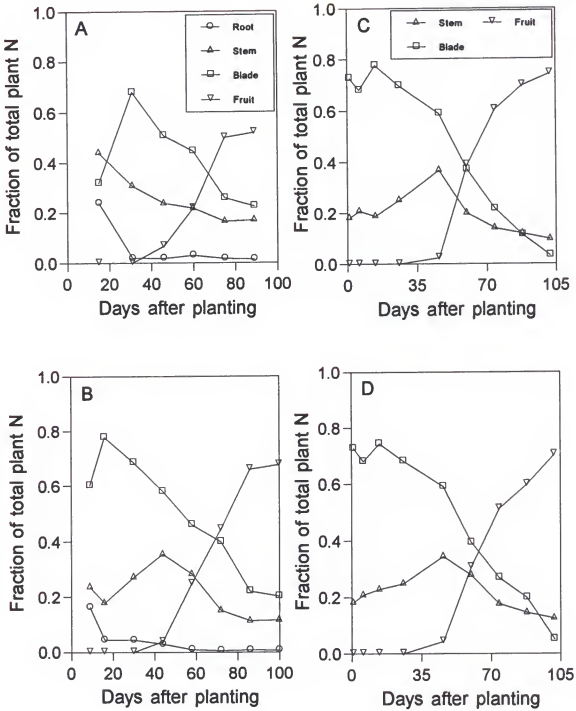


Fig. 5-13. Allocation of total plant N to root, stem, leaf, and fruit at a) Bradenton 1991; b) Bradenton 1994; c) Bradenton 1995 (N = 0 kg ha^{-1}); and d) Bradenton 1995 (N = 300 kg ha^{-1}).

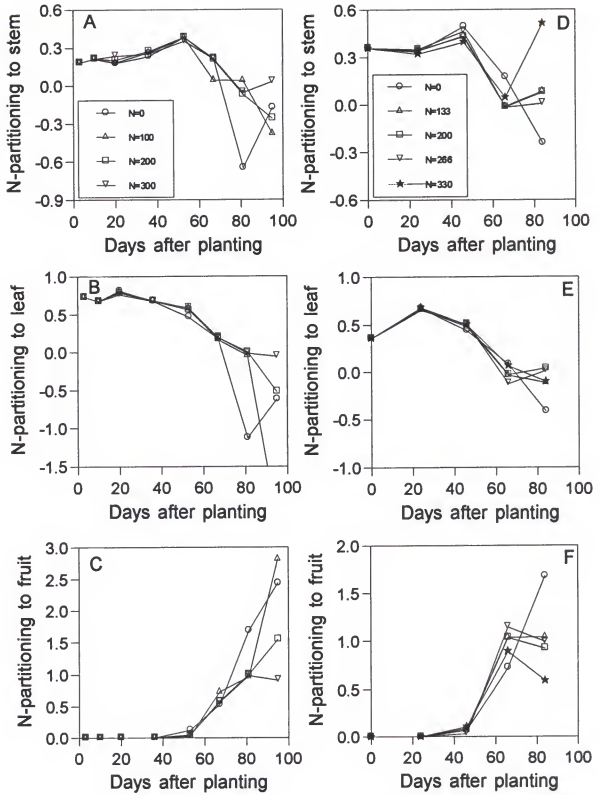


Fig. 5-14. Effects of N fertilizer rates on N partitioning to a) stem; b) leaf; and c) fruit at Bradenton 1995; and to d) stem ; e) leaf; and f) fruit at Gainesville 1996.

during fruit filling. High N-partitioning coefficients (>> 1.0) near the end of the growing season may be indicative of pronounced N-mining of both leaves and stems, due to N-stress. This also occurred at the lowest N-rate for Bradenton near the end of the growing season, but was not observed for Quincy.

Conclusions

Based on these results, it may be concluded that severe N-stress reduced LAI values, biomass, and fruit yield by 60-70%. Reductions in LAI were related to a decrease in leaf size and leaf number and caused a reduction in light interception from 0.8-0.9 (under optimal conditions) to 0.3-0.4. Reductions in RUE values under N-limiting conditions, on the other hand, were typically well below 30%, and could have been related to a decrease in N concentration of the leaves from 4 to 1.5%, and a concurrent reduction in leaf photosynthesis. The reduction in leaf photosynthesis was typically well below 30%. This could have been related to the increase in leaf thickness, which would allow relatively high photosynthetic rates (on a leaf area basis) under N-limiting conditions. Apparent N-fertilizer recovery decreased as N-rates increased, with values ranging from 0.61-0.96 and 0.36 to 0.74 for subirrigated and drip-irrigated crops, respectively. Nitrogen accumulation for a well-managed tomato is typically on the order of 140 to 200 kg N ha^{-1}, with roughly 70% of this amount being accumulated by the fruit. Based on the low N uptake observed for tomato during initial growth, it appears that the N use efficiency on coarse-textured soils may be increased by reducing the amount of preplant fertilizer to about 20%.

CHAPTER 6
DISTRIBUTION OF ROOTS, WATER, AND NITROGEN IN PRODUCTION BEDS

Introduction

The distribution of N and roots in production beds affects both plant growth and N use efficiency. Incongruence between N supply and N uptake typically result in either reduced plant growth or increased N losses. Polyethylene mulch can reduce N losses due to (excessive) rainfall. However, N losses may still be substantial, especially if irrigation water supply is not closely matched to actual crop water requirements. With the use of drip irrigation on coarse-textured soils, N can be readily displaced and may either accumulate at the edge of the wetting front or be leached below the root zone. With the use of subirrigation, on the other hand, the flow of water and solutes is predominantly upward and N losses to leaching appear to be relatively low. However, fluctuations in the perched water table's depth with subirrigation can still result in additional N losses and in root decay due to anaerobic conditions.

Although rooting characteristics of tomato are well-documented, it appears that inherent genetic and spatial variability can be appreciable. Variation in the efficiency of detecting or extracting very fine roots and root hairs may vary greatly between studies, depending on the methodology used. This makes the interpretation of experimental results even more complicated. Though these smaller roots may only account for a relatively

small fraction of the total root biomass, their contribution to overall water and nutrient uptake may be substantial.

With the use of the CROPGRO model, spatial distribution of water and solutes is simulated over time, assuming one-dimensional flow (a "tipping bucket approach"). However, this approach is not appropriate to simulate solute transfer for subirrigated crops. Rooting patterns for subirrigated crops also appear to be quite different from those for systems with a deep water table. As a result, CROPGRO-predicted distribution of both roots and solutes in production beds may be inaccurate.

The primary objectives of this chapter are to: (1) describe spatial and temporal distribution of water, roots, and N in tomato production beds; (2) outline effects of irrigation method and N rate on the rooting characteristics of tomato; and (3) define functional relationships between root length and root weight for tomato.

Materials and Methods

Root, soil N concentration, and soil moisture data for subirrigated crops were collected from experiments conducted at the Gulf Coast Research and Education Center (REC) in Bradenton (FL) during the spring season of 1995 on an Eaugallie fine sand (sandy, siliceous, hyperthermic, Alfic Haplaquods). Root, N, and soil moisture data for drip-irrigated crops also were collected during 1995 from experiments conducted at the Southwest Florida REC in Immokalee (spring), the North Florida REC in Quincy (spring and fall), and the IFAS Horticultural Unit of the University of Florida in Gainesville (spring). Respective soils were an Immokalee fine sand (sandy, siliceous, hyperthermic,

arenic Haplaquods), an Orangeburg loamy sand (fine-loamy, siliceous, hyperthermic, typic Paleudults), and a Millhopper fine sand (loamy siliceous, hyperthermic, grossarenic Paleudults). An overview of soil characteristics for these soils is presented in Appendix B (Tables 4 through 7).

Sampling dates and sample locations for roots are presented in Table 6-1. Root weights and root lengths of transplants were determined by carefully washing away the "plug mix" from the root system. After cleaning these samples, all lateral roots were excised and the total length of lateral roots was measured using the line intersect method (Tennant, 1975). Length of the taproot was measured with a ruler, and after root length determinations, roots were dried at 65°C prior to dry weight determinations.

For subsequent sampling dates, roots were extracted by either washing away the entire soil volume to a depth of 50 cm (method 1) and/or by excavating portions of the root system which had been delineated using a metal frame (method 2). During each excavation, first a volume of 10 cm square and 15 cm deep surrounding the tap root was excavated. Then a metal frame which was 22.5 or 30 cm wide for drip-irrigated crops and subirrigated crops, respectively, 45 cm long and 15 cm tall with 2 rows of 3 equal-sized compartments (15 x 15 x 15 cm or 11.3 x 15 x 15 cm, respectively) was positioned on the production bed, such that it covered exactly one quarter of the area occupied by the plant (Fig 6-1). Subsequently, the frame was driven into the beds to a depth of 15 cm and soil from each compartment ($\pm$ 0.0034 m^3) was excavated and stored in labeled buckets. Roots were then extracted from the soil by gently rinsing the excavated soil over a 5/64" round grain sieve (Seedburo Equipment Co., Chicago, IL). After removal of the soil,

Table 6-1. Overview of sampling dates and sample locations for roots during the 1995 growing season

Location	Treatment	Julian date	Days after planting	Sampling method
Bradenton	Transplants	55	0	Washing only
	300 kg N ha^{-1}	69	14	Method 1
	200 kg N ha^{-1}	81	26	Method 1
	200 kg N ha^{-1}	81	26	Method 2
	0 kg N ha^{-1}	115	60	Method 2
	200 kg N ha^{-1}	115	60	Method 2
	0 kg N ha^{-1}	143	88	Method 2
	100 kg N ha^{-1}	143	88	Method 2
	200 kg N ha^{-1}	143	88	Method 2
	300 kg N ha^{-1}	143	88	Method 2
Immokalee	Transplants	20	0	Washing only
	Conventional	54	34	Method 1
	Conventional	68	48	Method 1
	Conventional	82	62	Method 2
	Conventional	114	94	Method 2

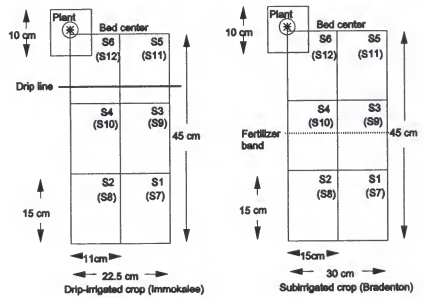


Fig. 6-1. Outline of root-sample positions for Immokalee and Bradenton during the 1995 growing season. Sample positions for the 0 to 15 cm soil depth are identified by numbers, with numbers in parenthesis referring to sample positions for the 15 to 30 cm soil depth.

roots and debris were carefully removed from the sieve and put in labeled plastic bags stored in an ice chest. They were refrigerated (and, in some cases frozen) upon return to the laboratory prior to further cleaning. During this subsequent cleaning, organic debris and grass roots were removed. Tomato roots were separated into tap root, large roots ($r >$ 1mm), medium-sized roots ($0.25 < r <$ 1mm), and fine roots ($r < 0.25$ mm). Samples were then stored in separate petri dishes, covered with water, and frozen ($\pm$ -20 C) until further analysis. After defrosting, root length was determined per size category. For larger samples (> 1.0 g), root lengths for medium and fine roots were determined from a representative subsample ($\pm$ 1.0 g). After root length determinations, roots were dried at 65°C prior to dry weight determinations.

Starting two to four weeks after transplanting, soil samples also were collected at a number of soil depths and positions throughout the beds approximately every four weeks. An overview of experimental locations, sample sites and sample depths is presented in Table 6-2. Samples were collected with a stainless steel sampling tube and were then stored in zip-lock bags in an ice chest. Upon return to the laboratory, samples were refrigerated, and processed within 24 to 48 h. During sample processing, a representative subsample of approximately 10 g moist soil was weighed and placed in a funnel on a folded paper filter (Whatman no. 5, Kent, U.K.). The soil was then leached with 50 mL of distilled water in increments of 10, 20, and 20 mL. This filtrate was collected in a glass beaker and used for electrical conductivity determinations using a model 31 conductivity bridge (YSI, Yellow Springs, OH). The same solution also was used for pH measurements, using a digital pH meter (Orion Research Corp., Cambridge,

Table 6-2. Overview of soil sampling dates and sample locations during the 1995 growing season for Bradenton, Gainesville, Immokalee, and Quincy.

Location	N-Treatment (kg N ha^{-1})	Julian date	DAP	Sampling location (cm from the edge)	Sampling depth (cm)
Bradenton	0, 100, 200, 300	69	14	20, 45	0-7.5, 7.5-15, 15-30, 30-45
	0, 100, 200, 300	81	26	20, 45	0-7.5, 7.5-15, 15-30, 30-45
	0, 100, 200, 300	129	74	20, 45	0-7.5, 7.5-15, 15-30, 30-45
	0, 100, 200, 300	157	102	20, 45	0-7.5, 7.5-15, 15-30, 30-45
G'ville	0, 133, 200, 266, 333	109	21	15, 30, 45, 60, 75	0-15, 15-30
	0, 133, 200, 266, 333	137	50	15, 30, 45, 60, 75	0-15, 15-30
	0, 133, 200, 266, 333	165	78	15, 30, 45, 60, 75	0-15, 15-30
Immok.	260	68	48	15, 30, 45, 60, 75	0-7.5, 7.5-15, 15-30, 30-45
	260	100	80	15, 30, 45, 60, 75	0-7.5, 7.5-15, 15-30, 30-45
	260	128	108	15, 30, 45, 60, 75	0-7.5, 7.5-15, 15-30, 30-45
Quincy	200	135	47	15, 30, 45, 60, 75	0-7.5, 7.5-15, 15-30, 30-45
	200	135	76	15, 30, 45, 60, 75	0-7.5, 7.5-15, 15-30, 30-45
Quincy (F)	0, 66, 166, 200, 266	242	43	30, 45, 60	0-7.5, 7.5-15, 15-30, 30-45
	0, 66, 166, 200, 266	109	63	30, 45, 60	0-7.5, 7.5-15, 15-30, 30-45
	0, 66, 166, 200, 266	109	84	45	0-7.5, 7.5-15, 15-30

MA). Subsequently, the soil was leached with an additional 50 ml of 2 M KCl , using increments of 10, 20, and 20 mL. This leachate was combined with the first extract, and acidified with 3 drops of concentrated sulfuric acid. Approximately 20 mL of this solution was stored in scintillation vials in a refrigerator until further analysis. Nitrate-N was determined using Rapid-Flow Analyzer technology (ALPKEM Corporation, 1989). Finally, the soil was rinsed with 3 volume increments of distilled water to remove any free KCl salt. After drying the samples at 105°C, total weights were recorded, and soil dry weight was calculated by subtracting the weight of the filter paper. All results were adjusted to a soil dry-weight basis.

Results and Discussion

Root Characterization and Root Distribution in Production Beds

An overview of root characteristics is shown in Tables 6-3 throughout 6-5, and in Fig. 6-2. At the time of transplanting, root length for a tomato plant was already on the order of 3 m per plant, and root dry weight accounted for approximately 30% of total plant dry weights. In Florida, "Speedling" trays are commonly used for transplant production. In this case the initial root mass is confined to a soil volume of 2.8 x 2.8 x 7.5 cm. With transplants, the tap root is typically broken off at 7-8 cm during handling, resulting in increased lateral branching and more superficial rooting characteristics (Portas and Dordio, 1980). The use of plastic mulch typically results in water condensation near

Table 6-3. Overview of tomato root dry weights for the 1995 growing season at Bradenton and Immokalee.

		Root weight (g plant^{-1})					Root weight distribution(%)			
	DAP	Tap	Large	Medium	Fine[2]	Total	Tap	Large	Medium	Fine
Bradenton	0	0.02		0.05		0.07	22.1		77.9	
	14	0.11		0.34		0.45	24.5		75.5	
	26	0.37	0.22	0.41	0.12	1.12	32.6	19.7	37.0	10.6
N=0*	60	1.70	5.59	4.54	2.26	14.09	12.0	39.7	32.2	16.0
N=200	60	2.30	4.23	3.68	3.38	13.53	17.0	31.1	26.9	25.0
N=0	88	1.39	4.36	3.74	2.46	11.95	11.7	36.5	31.3	20.6
N=100	88	1.94	6.29	6.28	2.68	17.19	17.2	36.6	36.6	15.6
N=200	88	2.47	3.99	5.52	5.69	17.66	14.0	22.6	31.2	32.2
Immokalee	0	0.01		0.03		0.03	21.2		78.8	
	34	0.25		0.59		0.83	29.6		70.4	
	62	1.08	1.60	5.06		7.74	13.9	20.7	65.4	
	94	2.78	5.95	2.66	3.94	15.34	18.1	38.8	17.4	25.7

* N-rate applied for production

[2] Root size categories: large:r > 1mm; medium 0.25 < r < 1 mm; small r < 0.25

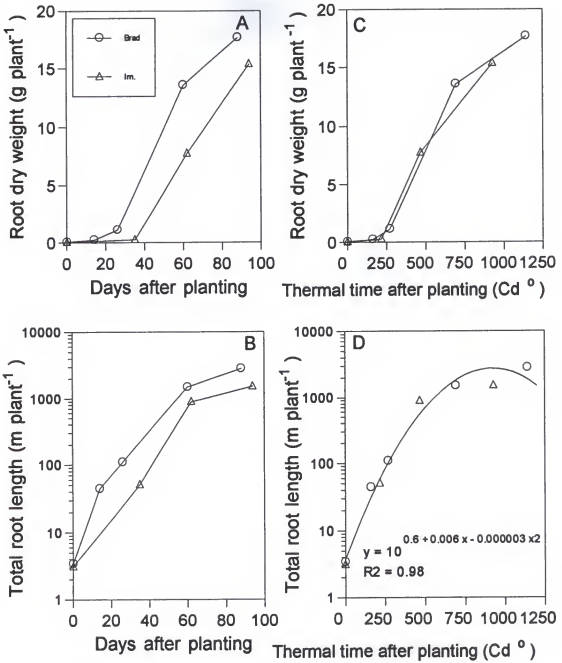


Fig. 6.-2. Root growth of tomato at Bradenton and Immokalee during the spring season of 1995: a) root dry weight plotted vs days after planting; b) total root length plotted vs days after planting; c) root weight plotted against thermal time; and d) total root length plotted against thermal time. Root lengths were fitted using an exponential regression equation(EM), expressing the log of the root length (y) as a function of thermal time (x).

Table 6-4. Overview of tomato root lengths for the 1995 growing season at Bradenton and Immokalee.

		Root length (m plant^{-1})					Root length (%)			
	DAP	Tap	Large	Medium	Fine	Total	Tap	Large	Medium	Fine
Bradenton	0	0.06		3.3		3.4	1.7		98.3	
	14	0.09		44		44	0.2		99.8	
	26	0.08	2.6	68	37	108	0.1	2.4	63.2	34.3
N=0*	60	0.08	32.7	659	425	1137	0.0	2.8	58.0	37.4
N=200	60	0.10	25.5	437	996	1460	0.0	1.7	30.0	68.3
N=0	88	0.05	19.2	637	868	1524	0.0	1.3	41.8	57.0
N=100	88	0.06	27.0	905	968	1900	0.0	1.4	47.7	50.9
N=200	88	0.04	25.6	849	1904	2779	0.0	0.9	30.5	68.5
Immokalee	0	0.05		3.1		3.2	1.6		98.4	
	34	0.07		50		50	0.2		99.9	
	62	0.08	9.9	870		880	0.0	1.1	98.9	
	94	0.08	42.2	228	1217	1488	0.0	2.8	15.3	81.8

* N-rate applied for production

Table 6-5. Overview of estimated tomato root radius and root-length to leaf-area ratio for the 1995 growing season at Bradenton and Immokalee.

		Root radius (mm)				Root length: Leaf area ratio
	DAP	Tap	Large	Medium	Fine	(cm root [cm^2 leaf]$^{-1}$)
Bradenton	0	0.8		0.22		14.4
	14	1.7		0.16		21.5
	26	3.2	0.48	0.14	0.11	9.7
N=0 *	60	7.8	0.67	0.15	0.09	13.8
N=200	60	7.4	0.66	0.16	0.12	5.3
N=0	88	8.1	0.78	0.14	0.11	6.1
N=100	88	8.9	0.79	0.15	0.10	14.5
N=200	88	11.4	0.64	0.14	0.11	14.2
Immokalee	0	0.7		0.16		21.0
	34	2.7		0.19		7.4
	62	5.7	0.65	0.14		13.9
	94	9.0	0.61	0.19	0.11	14.0

* N-rate applied for production

the soil-mulch interface, and results in further proliferation of fine roots near the surface (Wien et al., 1987).

Total root weight increased from 0.03 to 0.07 g per plant at transplanting to 15-18 g per plant at crop maturity; similar values were reported by McNeal et al. (1995). Although tap roots and large lateral roots accounted for a substantial portion of the total root weight (Table 6-3), their contribution to total root length was relatively minor (Table 6-4). Fine-root weights were not recorded separately during initial growth, but their eventual contribution to final root weight (26-32%) appeared to be relatively small compared to their eventual contribution to final root length (69-82%). It thus may be concluded that the most important functions of larger roots are plant-anchorage and lateral water transport. The prime function of medium and fine roots, on the other hand, appears to be water and nutrient uptake.

Total root length and root weight appeared to increase more rapidly at Bradenton compared to Immokalee. However, plotting root weight or length as a function of thermal time resulted in overlapping curves, with observed differences being most likely related to lower temperatures at Immokalee (the crop here being planted one month earlier then at Bradenton). Total root length increased from approximately 3 m per plant at transplanting to 1500 to 2800 m per plant at harvest (Table 6-4), which compares favorably with values reported by Portas and Dordio (1980). The increase in root weight appeared to follow a logistic growth curve, whereas total root length appeared to increase almost exponentially during the first 9 weeks after transplanting (Fig. 6-2: note the log scale, with a linear increase on the figure being indicative of an actual exponential increase). The ratio of root

length to leaf area remained fairly constant throughout the growing season, with overall values being on the order of 14-21 cm root per cm^2 of leaf (Table 6-5). However, the ratio appeared to drop during the rapid growth phase, before increasing again towards the end of the growing season.

N-stress resulted in reduction of late-season root length and root weight. However, root to shoot ratio for the zero N-treatment was 0.072 g root dw [g shoot dw]$^{-1}$, which is significantly higher than values for the 100 and 200 N-rates, which were 0.0037 and 0.0025 g root dw [g shoot dw]$^{-1}$, respectively. It therefore could be concluded that severe N-stress results in increased partitioning of dry matter to the roots. This supports the hypothesis of Richards et al. (1979) that there is a functional equilibrium between roots and shoots. This theory proposes that, under severe N-stress, the partitioning of N to roots (which have a much lower N content compared to leaves) will be favored, resulting in increased N uptake. The latter may then once again favor the formation of additional leaves. This mechanism could thus allow maximum plant growth under N-limiting conditions.

Root radii were estimated using the formula:

$$r = \sqrt{\frac{FW}{\pi L}} \qquad (1)$$

where r = root radius (mm); FW= root fresh weight; and L= root length (mm), assuming a specific density for roots of unity. Average diameter of the tap roots increased from 0.7-0.8 mm at transplanting to 9-11 mm at harvest (Table 6-5). The size classes of all other roots, on the other hand, appeared to remain fairly constant. Root length per gram dry

weight of roots were on the order of 6-12, 66-150, and 300-350 m g^{-1} for large, medium, and fine roots, respectively.

Root distributions within the production bed for subirrigated plants at Bradenton are presented in Figs. 6-3a to d. Four weeks after transplanting, most roots remained within 5-10 cm of the plant. This was probably related to the shape of the initial root system at transplanting (roots at transplanting being confined within a narrow cone approximately 7 cm long and 1 to 3 cm wide). However, tomato roots also typically reached the bed edges within 4 to 5 weeks of transplanting. Over time the lateral and vertical spread became more pronounced (Fig. 6-3 b and d), as shown by dispersion of root-distribution contour lines. N-stress, on the other hand, appeared to reduce lateral root growth and favored the formation of a somewhat deeper root system (Fig. 6-3c). The presence of a fertilizer band (Fig. 6-3b) appeared to slightly enhance root growth. Similar enhancement for drip-irrigated systems at Immokalee (Fig. 6-3c and f) could have been associated with more favorable water contents throughout the season. It is also shown by a relative increase in rooting densities at a distance of 20 cm from the bed center.

Maximum observed root densities in the upper 15 cm of the bed ranged from 2.6-5.0 cm root [cm^3 soil]$^{-1}$ near the bed center to 0.7-1.2 cm root [cm^3 soil]$^{-1}$ near the edge of the production bed. This agrees favorably with values reported by Sanders et al. (1989). Corresponding values for the 15 to 30 soil depth were 0.6-1.0 cm root [cm^3 soil]$^{-1}$ and 0.3-0.4 cm root [cm^3 soil]$^{-1}$. The rapid decay in root density with increasing soil depth may be related to the presence of a spodic horizon and a shallow water table. Clark et al. (1989a) reported that, for drip-irrigated tomato, root densities were highest near the drip

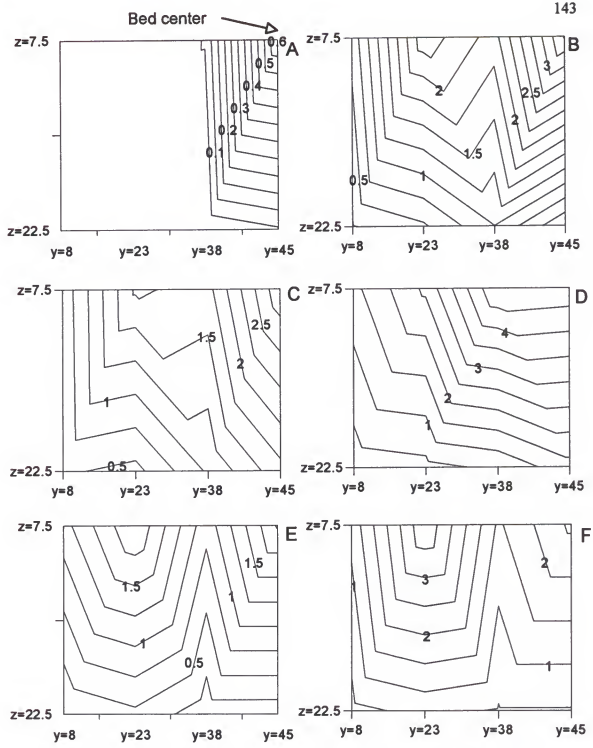


Fig. 6-3. Root distribution for a) Bradenton, 4 weeks after transplanting (N=200 kg/ha); b) Bradenton, 9 weeks after transplanting (N=200 kg/ha); c) Bradenton, 13 weeks after transplanting (N=0 kg/ha); d) Bradenton, 13 weeks after transplanting (N= 200 kg/ha); e) Immokalee, 9 weeks after transplanting; and f) Immokalee, 13 weeks after transplanting. Contour lines express root length in cm per cm^3 of soil.

line. In their study observed root densities were on the order of 2-7, 1-2, and 0-1 cm root $[cm^3 soil]^{-1}$ for the 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm soil depths, respectively. The decrease in root density for production systems with a deep water table appears to be more gradual (Singh et al., 1989; Tan and Fulton, 1985), with root length densities near the surface also being much lower (Giardini et al, 1988a). Under deep water table conditions, root densities decreased from 1-2 to 0.5-1 cm root $[cm^3 soil]^{-1}$ at the 10 and 90 cm soil depths, respectively (Giardini et al., 1988a; Jackson and Bloom, 1990). Portas and Dordio (1980) reported that root growth of tomato is typically confined by a clay pan. The presence of a spodic horizon, very acidic subsoil conditions, and the fluctuating water tables typically associated with clay pans or spodic horizons may thus form a physical barrier for root growth, resulting in root concentration near the soil surface.

Soil Moisture Patterns in Production Beds

Soil moisture distribution for drip-irrigated crops on a loamy (Quincy), and a sandy soil (Immokalee) are shown in Fig. 6-4a through d. In the top 10-15 cm of the sandy soil (Fig. 6-4a and b) a relatively narrow zone was wetted by the drip tube, with a lateral moisture gradient that was fairly steep. The parallel lines at the 12 to 22 cm soil depth (Fig. 6-4a) suggest lateral spread of water occurred below the mulched layer perhaps in conjunction with a traffic-compacted layer. The lateral distribution of soil moisture appeared to be greater for the loamy soil (Fig. 6-4c, where the slopes of the contour lines in the upper 20 cm of the soil profile were not as steep). The relatively "dry" spots on the

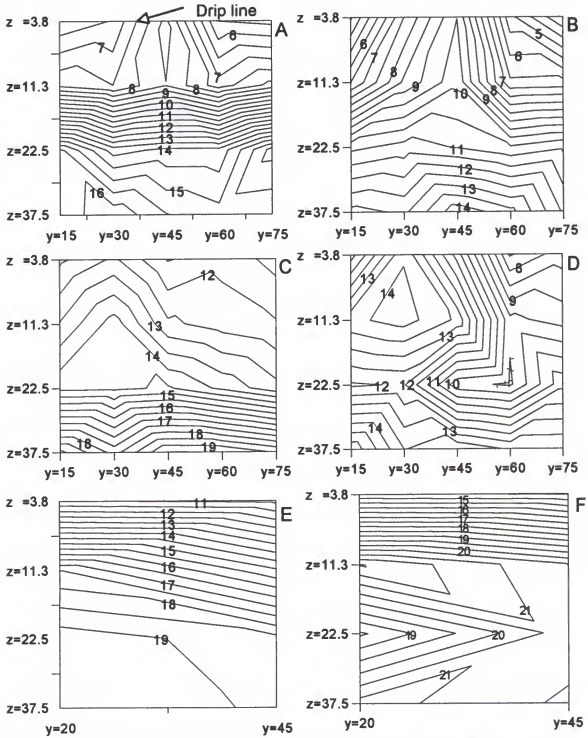


Fig. 6-4. Soil moisture-content contour plots for drip-irrigated tomato at Immokalee during 1995 at a) 7 weeks after transplanting and b) 11 weeks after transplanting; for drip-irrigated tomato at Quincy during 1995 at c) 7 weeks after transplanting; and d) 11 weeks after transplanting; and for subirrigated tomato at Bradenton during 1995 at e) 4 weeks after transplanting; and f) 10 weeks after transplanting.

the opposite side of the bed from the drip tube are noteworthy, since N and other solutes typically accumulate at the edge of the emitter wetting front.

Soil moisture distribution for a subirrigated crop at Bradenton is shown in Figs. 6-4e and f. For the subirrigated crop only one side of the bed was sampled, at two depths in the bed. Moisture distribution in the upper part of the bed appeared to be quite uniform. A moisture gradient at greater soil depth suggested possible lateral flow in this instance, as well.

Distribution Patterns for Nitrogen and Soluble Salts in Production Beds

Distribution of solutes in production beds can be shown using electrical conductivity (EC) contour plots. With drip irrigation, solutes accumulate near the edge of the wetting front, resulting in increased EC values at the corner of the bed furthest away from the drip line (Fig. 6-5a to d). With the use of fertigation (Immokalee) only a fraction of the fertilizer was applied at transplanting and, as a result, solute concentrations early in the season were lower (Fig. 6-5a) compared to those at Quincy (Fig. 6-5c). Due to the coarse soil texture, solutes were also quite prone to leaching, which could have resulted in overall lower solute levels. With subirrigation the predominant flow of water is upward, and all the fertilizer is applied in narrow bands approximately 20-25 cm from the bed center (Fig. 6-5 e and f). The radial movement of solutes observed here is most likely related to outward diffusion of solutes from the fertilizer band over time.

An overview of the effect of N-rate on soil NO_3-N concentrations for subirrigated

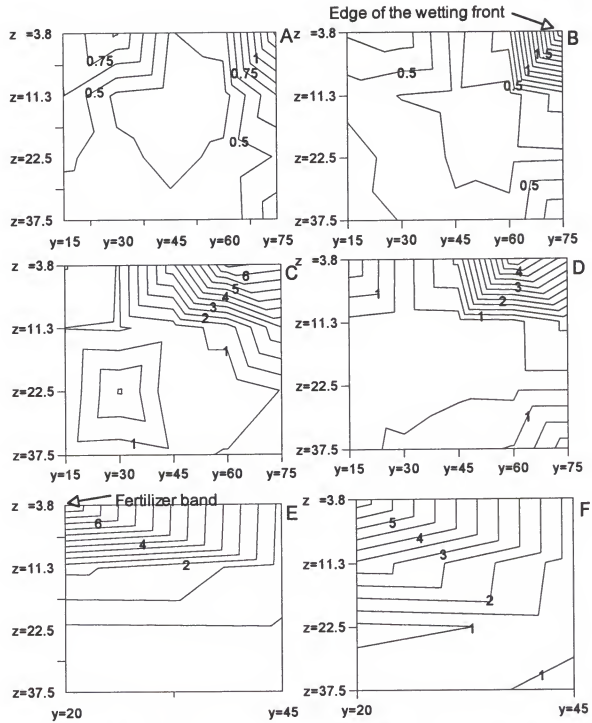


Fig. 6-5. Electical conductivity contour plots for drip-irrigated tomato at Immokalee during 1995 at a) 7 weeks after transplanting and b) 11 weeks after transplanting; for drip-irrigated tomato at Quincy during 1995 at c) 7 weeks after transplanting; and d) 11 weeks after transplanting; and for subirrigated tomato at Bradenton during 1995 at e) 4 weeks after transplanting; and f) 10 weeks after transplanting. Contour lines express electrical conductivity in dS m^{-1}.

crops is presented in Table 6-6. Based on the values in this table, it may be concluded that "background" levels of NO_3-N for the 4 and 38 cm soil depths were on the order of 4 and 1.5 ppm NO_3-N, respectively. Plant uptake in the upper soil layer appeared to further reduce NO_3-N concentration to approximately 1-2 ppm NO_3-N. At greater soil depths "steady state" NO_3-N concentrations appeared to be even lower, possibly due to subsequent denitrification. Increase in N-rate from 0 to 300 kg N ha^{-1} resulted in an increase in NO_3-N in the immediate vicinity of the fertilizer bed, from 4.5 to 401 ppm. However, this increase in NO_3-N readily dissipated with increasing distance from the fertilizer band. As a result, NO_3-N concentrations remained typically below 10 ppm at a radial distance of 25 cm or more from the fertilizer band (Fig. 6-6e).

Table 6-6. Overview of NO_3-N distribution [1] in production beds at Bradenton (1995)

N-rate	Soil depth	Fertilizer band Days after planting				Bed center Days after planting			
(kg N ha^{-1})	(cm)	14	26	74	88	14	26	74	88
N=0	4	4.5±0.4	4.5±1.8	1.5±0.0	2.3±0.3	4.1±0.9	4.5±1.8	1.5±0.0	2.3±0.3
	11	1.9±0.3	3.0±1.9	1.3±0.2	2.2±0.0	2.6±0.1	4.6±2.7	1.7±0.1	2.2±0.0
	22	1.1±0.4	1.3±0.3	1.3±0.1	1.9±0.0	1.6±0.2	1.3±0.3	1.6±0.1	1.9±0.0
	38	1.4±0.0	1.2±0.2	1.4±0.0	1.8±0.1	1.4±0.0	1.2±0.3	1.5±0.2	1.8±0.1
N=100	4	198±22	103±25	1.8±0.0	2.0±0.0	7.4±0.4	5.7±2.3	1.6±0.0	2.2±0.3
	11	66±22	42±20	1.6±0.1	2.3±0.1	3.7±0.5	2.7±1.7	1.7±0.1	2.2±0.0
	22	5±3.8	1.8±0.2	1.8±0.4	1.7±0.1	1.0±0.2	1.4±0.3	2.0±0.0	1.8±0.2
	38	3±1.2	2.2±0.8	2.0±0.3	2.0±0.1	1.3±0.6	2.0±0.4	3.0±0.9	1.8±0.2
N=200	4	210±54	227±26	32±30	5.6±3.7	5.1±1.0	5.6±1.6	3.9±0.7	1.9±0.1
	11	73±14	100±28	4.4±2.5	2.4±0.5	5.4±1.1	3.5±1.8	15 ±11	1.9±0.4
	22	3.7±2.1	8.1±5.1	2.0±0.0	1.7±0.0	1.1±0.4	1.4±0.4	12 ±10	1.9±0.0
	38	6.0±2.5	1.6±0.6	3.2±1.2	2.3±0.4	1.5±0.5	1.3±0.3	3.9±1.2	1.9±0.1
N=300	4	401±81	274±40	27±0.0	53 ±27	6.5±1.8	4.9±0.3	6.2±0.1	10 ±8.2
	11	185±36	157±32	3.2±0.2	3.2±1.0	3.8±0.8	3.5±0.5	1.5±2.0	3.6±1.0
	22	13 ±4.5	25±15	3.7±0.3	2.8±1.0	1.7±0.4	1.0±0.2	1.9±0.0	1.8±0.3
	38	9.1±2.1	2.2±0.5	17 ±12	2.0±0.1	1.5±0.1	1.9±0.9	3.3±0.9	1.9±0.1

[1] Values are in ppm NO3-N per and results are adjusted to a soil dry weight basis.

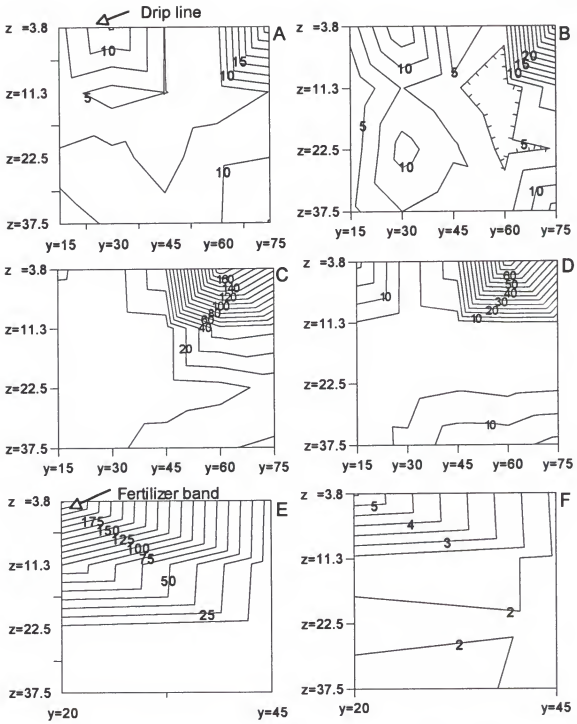


Fig. 6-6. Soil nitrate-N contour plots for drip-irrigated tomato at Immokalee during 1995 at a) 7 weeks after transplanting and b) 11 weeks after transplanting; for drip-irrigated tomato at Quincy during 1995 at c) 7 weeks after transplanting and d) 11 weeks after transplanting; and for subirrigated tomato at Bradenton during 1995 at e) 4 weeks after transplanting and f) 10 weeks after transplanting. Contour lines express soil NO_3-N concentrations in ppm.

For N-rates below 200 kg N ha^{-1}, NO_3-N concentrations in the soil returned to background levels before the end of the growing season. For the higher N-rates, however, NO_3-N concentrations near the fertilizer band remained on the order of 10 ppm, while NO_3-N concentrations at all other locations in the bed approached background levels. Removal of the plastic mulch at the end of the production season would expose the bed to rainfall once more. As a result, residual NO_3-N would become susceptible to leaching, and "steady state" background levels for NO_3-N should further drop to the 0-1 pm range.

An overview of the effect of N-rate on soil NO_3-N concentrations for drip-irrigated crops at Gainesville and Quincy during the 1995 growing season is presented in Tables 6-7 and 6-8. At Quincy all fertilizer was applied preplant, whereas at Gainesville 40% was applied preplant, with the remainder being applied in ten weekly applications via the irrigation water. The use of fertigation resulted in relatively high mid- and late-season NO_3-N concentrations (Table 6-7) compared to when all fertilizer was applied preplant (Table 6-8). The occasionally high NO_3-N concentrations observed for the side of the bed furthest from the drip line (Fig. 6-6b and d) may be related to the accumulation of NO_3-N near the wetting front. However, the exact location of this zone of NO_3-N accumulation is prone to spatial variability, and may significantly vary between replicates. This is shown by the high standard error values in the tables. Based on the values presented in Tables 6-6 and 6-8, fluctuations in NO_3-N concentrations in time and space for drip-irrigated crops appeared to be relatively small compared to trends for subirrigated crops, with the exception of NO_3-N accumulation at the edge of the wetting front. With drip irrigation, convective flow of solutes including NO_3-N is outward, resulting in a radial dispersion of

Table 6-7. Overview of NO_3-N distribution in production beds at Gainesville (1995)

		Sample location (cm from bed edge)														
		15			30			45			60			75		
N-rate	Soil depth	Days after planting			Days after planting			Days after planting			Days after planting			Days after planting		
(kg N ha^{-1})	(cm)	21	50	78	21	50	78	21	50	78	21	50	78	21	50	78
N=0 [1]	7.5	3.9	1.9	1.5	1.6	1.5	4.5	3.0	7.8	4.5	1.5	4.1	2.3	2.2	9.0	4.5
	22.5	2.1	1.9	1.5	1.9	2.4	4.5	2.2	3.7	4.5	2.7	5.0	2.3	2.2	2.5	4.5
N=133	7.5	13 ±2.4	3.2±1.1	1.5±0.0	7.3±1.5	4.9±1.4	4.5±1.8	7.6±1.1	3.9±1.5	6.2±3.4	13 ±2.5	6.2±3.4	2.3±0.3	13 ±0.9	11 ±4.1	4.5±1.8
	22.5	6.2±1.4	2.5±0.7	1.5±0.0	3.3±0.7	5.5±1.4	4.5±1.8	5.2±1.0	2.4±05	2.7±0.6	6.5±1.0	2.7±0.6	2.3±0.3	9.6±1.3	8.5±6.3	4.5±1.8
N=200 [1]	7.5	7.7	8.0	1.6	4.1	25	1.4	5.6	19	1.5	9.2	18	2.9	12	4.3	51
	22.5	5.8	2.9	1.7	5.7	29	2.9	6.1	24	1.8	8.2	4.6	0.3	7.8	2.7	5.8
N=266	7.5	26 ±9.2	11 ±0.8	13 ±8.4	7.7±1.3	15±3.0	2.7±0.7	8.0±1.0	19 ±5.9	9.9±4.0	16 ±1.8	1.5±0.0	18 ±8.1	28 ±14	51 ±2.0	15 ±4.5
	22.5	4.9±1.8	7.1±2.7	13±8.2	7.0±3.5	18±4.5	2.1±0.2	7.8±0.4	22 ±1.9	5.6±2.9	9.8±1.5	1.5±0.0	12 ±4.1	11 ±2.1	6.1±1.2	5.5±1.5
N=333 [1]	7.5	14	11	3.9	8.2	32	1.9	8.5	2.3	19	14	47	10	80	19	67
	22.5	11	12	5.5	6.1	36	2.4	7.8	2.3	16	5.2	9.3	15	14	6.9	22

[1] Measurements were not replicated, so standard error could not be calculated.

Table 6-8. Overview of NO_3-N distribution in production beds at Quincy (1995, Fall)

N-rate	Soil depth	Drip line (x=30 cm) Days after planting		Bed center (x=45 cm) Days after planting			Opposite side (x=60 cm) Days after planting	
(kg N ha^{-1})	(cm)	43	63	43	63	84	43	63
N=0	4	2.5±1.4	4.4±0.5	2.7±1.2	4.3±0.7	4.0±0.5	7.0±5.6	3.0±0.7
	11	2.0±1.1	4.2±0.5	2.4±1.3	4.6±1.1	4.0±0.2	3.0±1.8	2.8±0.4
	22	2.3±1.1	4.4±0.4	2.2±1.4	3.0±0.6	3.7±0.4	2.4±1.2	2.9±0.6
	38	2.4±1.3	4.3±0.3	2.6±1.5	2.8±0.9		2.3±1.3	2.7±0.5
N=67	4	3.9±2.6	5.0±0.2	2.3±1.0	4.9±0.3	4.4±0.1	12 ± 11	12 ±7.8
	11	2.2±1.1	4.4±0.7	2.2±0.8	4.8±0.4	4.0±0.2	5.5±2.1	5.3±2.1
	22	2.1±1.1	4.7±0.7	2.0±0.9	4.7±1.0	4.5±0.6	4.0±1.3	4.5±1.1
	38	2.3±1.0	4.5±1.2	2.1±1.0	4.4±1.1		4.3±0.8	4.1±1.1
N=133	4	2.3±1.2	5.2±2.2	2.5±1.2	4.5±1.1	4.1±0.4	6.6±4.9	5.1±0.0
	11	2.2±1.0	4.5±1.0	2.4±1.2	4.3±0.7	3.9±0.4	2.9±1.3	5.2±0.2
	22	2.5±1.1	4.5±0.9	2.5±1.0	4.4±0.8	3.9±0.5	3.4±1.4	5.1±0.3
	38	3.1±0.9	5.1±0.4	4.5±1.8	4.7±0.9		8.9±5.4	5.9±0.2
N=200	4	8.8±6.0	3.8±1.3	4.8±2.8	3.6±0.6	5.6±0.9	66 ±47	9.0±4.3
	11	3.0±0.8	3.5±0.9	2.8±1.3	3.4±0.6	5.8±1.7	41 ±24	4.8±0.1
	22	3.0±0.7	3.6±0.7	2.5±0.9	3.5±0.7	6.8±2.5	27 ±19	4.0±0.6
	38	3.6±0.8	3.1±0.3	3.7±1.5	3.8±0.9		22 ±11	4.4±1.5
N=267	4	2.6±0.7	3.6±0.7	2.8±0.9	3.6±0.9	4.5±0.4	21 ±19	74 ±72
	11	2.6±0.8	3.6±0.5	2.4±0.9	3.5±0.6	4.2±0.4	6.1±3.7	14 ±11
	22	2.7±0.8	3.3±0.6	3.1±1.0	3.4±1.0	4.0±0.2	27 ± 23	4.9±2.5
	38	3.8±0.8	3.1±0.7	5.1±1.8	3.4±1.0		16 ±7.0	6.1±3.7

solutes throughout the profile. Irrigation management thus becomes critical with respect to N movement. Over- irrigation typically results in displacement of NO_3-N beyond the active root zone, and under- irrigation results in nitrate-N accumulation in dry pockets near the edges of the bed.

On coarse-textured soils, lateral movement of water is limited and rewetting of dry pockets formed near the bed edges may not occur. As a result, nitrate-N may stay "high and dry" (G. Hochmuth, personal communication) until the plastic mulch is removed, after

which it is typically lost due to leaching. Roots will typically proliferate at locations where there is ample supply of both water and nutrients. Root growth in dry pockets may be limited due to low moisture contents and the associated high temperatures; NO_3-N located in these pockets thus may no longer be available for further plant uptake.

With subirrigation of fully mulched beds, water and solute flux is predominantly upward. In this case, lateral NO_3-N movement mainly occurs as a result of diffusion. However, high-intensity rainfall events may result in saturated soil conditions even near the surface. This may then result in "fall-out" (vertical movement of solutes due to the high specific gravity of concentrated salt solutions) of NO_3-N as described by Bonczek and McNeal (1996). Under these conditions denitrification losses may also become appreciable, resulting in further NO_3-N loss. The temporary anaerobic conditions may also result in increased root senescence and root decay.

Conclusions

Under typical Florida conditions, it appears that approximately 80% of the total root weight and root length for tomato is confined to the upper 15 cm of the production bed. Although initial root length for tomato transplants was already on the order of 3 m per plant, most of these roots were confined to a relatively small zone and the root system typically only reached the edges of the bed by 4 to 6 weeks after transplanting. Maximum total root length appeared to be on the order of 1500 to 3000 m per plant, with most of this length concentrated near drip emitters or fertilizer bands and in the upper 15 cm of the production beds. Under most experimental conditions, root growth below the 30 cm soil

depth appeared to be severely restrained by soil conditions unfavorable to root growth. Based on these findings it may be concluded that, once N is moved below a soil depth of 30 cm in production bed, it may no longer be (readily) available for plant uptake. To attain high N use efficiencies, on the other hand, management of both water and nutrients must be such that soil moisture and NO_3-N levels are adequate and yet not excessive in the associated soil volume.

With subirrigation, depth to the water table must be maintained within 40-50 cm of the soil surface (to reduce N-losses due to fertilizer drop-out and denitrification), and fertilizer bands should be placed approximately 20-25 cm away from the plant (since initial lateral spreading of the root system is limited). With the use of drip irrigation on coarse-textured soils, only a fraction of the fertilizer (preferably 20% or less) should be applied during bed preparation (since N-uptake of the crop during the first month after transplanting is typically well below 10 kg N ha^{-1} as shown in Fig. 5-12). Excessive initial N-application for drip-irrigated crops on coarse-textured soils therefore can result in increased N leaching and thus in reduced ANR values (Table 5-9; compare results of data sets for Gainesville with those of Hochmuth). The potential for N leaching is further increased if water supply is based on pan evaporation instead of tensiometer readings. Use of drip irrigation on coarse-textured soils thus requires "state of the art" water and nutrient management.

Deviations from optimal water- and N- supply will typically result in irreversible yield reductions and in decreases in both water- and nutrient-use efficiencies. Since fine-textured soils typically have greater water holding capacities, vertical movement of both

water and nutrients is relatively lower. As a result, irrigation intervals and the fraction of the fertilizer applied preplant may be increased. However, the use of fertigation and frequent irrigation may still be required for optimal yields and high N use efficiencies.

CHAPTER 7
FRUIT AND YIELD CHARACTERISTICS OF FIELD-GROWN TOMATO

Introduction

Fruit and yield characteristics of field-grown tomato are controlled both by genetic traits and environmental conditions. Extensive research has resulted in the development of high-yielding varieties for a range of specific, and sometimes even adverse, growing conditions. In addition to genetic traits, yield levels are also determined by radiation, temperature, and CO_2 concentrations; water supply and water quality ; nutrient supply and nutrient imbalances; biotic stress factors (pests and diseases); and abiotic stress factors (presence of toxic compounds).

Although the prediction of total grain dry weight appears to be highly important for most agronomic crops, this may not hold true for field-grown tomato. For modeling results to be meaningful or useful for producers, extension workers, and economists, additional model outputs including fruit fresh weight, fruit size distribution, fruit quality, and fruit maturity must be included as well. One of the main challenges to adapting existing crop-growth models for fresh-market vegetables thus may be the successful incorporation of alternative yield properties into an existing crop model structure.

The development of appropriate model components may require additional information on the effects of growth factors on fruit development, fruit yield, and fruit

quality. The eventual incorporation of such features, however, should allow use of these models to evaluate the effects of crop management, environmental regulations, and marketing strategies on the viability of commercial production for field-grown tomato. The models thus could assist scientists and policy-makers in identifying successful strategies for field-grown tomato production that could maximize economic returns while minimizing financial risk for producers and the costs of externalities to society. The primary objectives of this chapter are to: (a) describe fruiting characteristics of field-grown tomato; (b) outline effects of both water stress and N-stress on fruit growth and development; (c) define functional relationships that describe fruit size, fruit weight, and dry matter content over time; and (d) outline how these relationships could be used to develop a marketable-fruit routine for field-grown tomato in the CROPGRO model.

Materials and Methods

Experiments involving several tomato cultivars were conducted between 1991 and 1996 at a number of locations in Florida. Experimental locations, along with information on cultural practices and names of the tomato varieties used, were presented in Table 3-1. Additional information on specific yield characteristics was compiled for growth studies conducted at (a) the Gulf Coast REC at Bradenton in 1994 and 1995; (b) the University of Florida Horticultural Unit at Gainesville in 1995 and 1996; (c) the Southwest Florida REC at Immokalee in 1995; (d) and the North Florida REC in Quincy in 1995. The numbers of lateral branches (>5 cm in length) and flower clusters were counted throughout the growing season at all locations, but only end-of-season values are presented here. Tomato

fruit set was only determined two weeks before final harvest during the 1994 growing season in Bradenton. Fruit set was assumed to have occurred only if fruit size was greater than 10 mm. Fruit set for a specific fruit cluster number for the main stem, lateral shoots originating from the main stem (first-order laterals), and their subsequent side-shoots (second-order laterals) were calculated separately. Opposite wedges from 5 to 10 fruits were homogenized in a food blender. Approximately 50 mL of this blended fruit pulp was dried for 48 hours at 70 ^{0}C and used for determination of dry matter percentage of the fruit.

During the 1995 and 1996 growing seasons at Gainesville, 40 fruits were labeled six weeks after transplanting, and the fruit size of individual fruits was recorded weekly. During the 1996 growing season, an additional 120 fruits were labeled for water-stressed plants (irrigation cutback treatments CB1 and CB2) and for plants within the zero-N plots. Each week six fruits per treatment were harvested and used for fresh and dry weight determinations. In addition to the samples collected during the 1995 and 1996 growing seasons at Gainesville, additional samples were collected at Bradenton (1995), Gainesville (1995 and 1996), and Quincy (1995) twelve weeks after transplanting. However, instead of using tagged fruits, approximately eighty fruits ranging in diameter from approximately 3 to 80 mm were collected at one point in time.

Fresh fruit weights of the fruits for which only the fruit diameter had been measured were subsequentially calculated using the following empirical relationship:

$$FW(r) = FC \cdot \frac{4\Pi}{3} \cdot r^3 \qquad (1)$$

where FW(r) = fruit fresh weight expressed as a function of fruit radius; FC= fruit coefficient, a correction factor to account for the effects of specific gravity and of slight deviations from a perfectly spherical shape of the fruit; and r = average fruit radius. Assuming perfectly round fruits the values for FC would range between 0.93 and 0.97 (Bussieres, 1993). Slightly flattened and oblong fruits, on the other hand, would have FC values of approximately 0.90 and 1.05, respectively. The value of FC is thus mainly controlled by cultivar but may also be affected by growing conditions. The value of FC for a given cultivar was fitted by increasing an initial FC value of 0.90 by increments of 0.01 until the x-coefficient of the linear regression of predicted vs actual fruit weights for sampled fruits approached unity .

The relation between fruit dry matter content and fruit radius can be defined as follows:

$$DMP(r) = DMP_{min} + \alpha\left(\exp^{-\beta * \frac{r}{r_{max}}}\right) \qquad (2)$$

where DMP(r) = the dry matter percentage (DMP) of the fruit as a function of fruit radius (r); DMP_{min} = the lowest value of the DMP (which typically occurs at fruit maturity); α= the difference between the maximum value of the dry matter percentage (DMP_{max},which is around 12 to 14% at the time of anthesis) and DMP_{min}; β= a time constant (which depends on environmental conditions); and r_{max} = maximum fruit radius (values of this coefficient may range between 50 and 90 mm, depending on the genetic traits of the cultivar). The coefficients for equation 2 were determined for the separate data sets, by using non-linear regression analysis (SAS Institute, Cary, NC).

The relationship between fruit dry weight and fruit radius was obtained by combining equations 1 and 2. It can be defined as follows:

$$DW(r) = FW(r) * DMC(r) \qquad (3)$$

where DW(r) = fruit dry weight as a function of fruit radius and DMC= dry matter content (which is DMP/100).

Averaged daily temperatures were used to calculate accumulated heat units after anthesis, with fruit diameter being related to degree days for the separate treatments using a quadratic regression equation assuming a base temperature for fruit development of 10 °C (Wolf et al., 1986). Fruit fresh and dry weights were plotted as a function of fruit diameter. The upper and lower limits of harvest categories as defined by the United States Standards for Grades of Fresh Tomatoes (United States Department of Agriculture, 1984) were used in combination with equations 1-3 to calculate corresponding fresh and dry weights of the standard fruit-size categories.

Effects of the above treatments on weight partitioning between seeds and fruit pulp were also evaluated by determining seed and pulp weights for 10-20 fruits ranging in size from 50 to approximately 300 g. Seeds were excised manually from sliced fruits. Seed samples then were soaked for 48 hours in water and, after degradation of the gelatinous film covering the seeds, were washed with distilled water while resting on top of a fine sieve. After rinsing and blotting the seeds between tissue paper, seed number and fresh seed weights were recorded. Finally, seeds and fruit pulp samples were dried in an oven

at 70°C for 48 hours, with recorded dry weights being used for determination of the dry matter contents of both seeds and fruit pulp.

Absolute and relative growth rates were calculated from both predicted and observed fruit weights. However, the use of a large sample size (n=40) appeared to be desirable. Experimental variability when using a smaller sample size (n=6) at times "masked" subtle time trends in fruit development.

Average LAI values (LAI_{max}) during the six weeks prior to fruit harvest were used to calculate the amount of intercepted solar radiation during this period, via the following equation:

$$Rad_{abs} = (1 - \exp^{-k \cdot LAI}) \qquad (4)$$

where RAD_{abs}= the amount of intercepted radiation and k= light extinction coefficient, for which a value of 0.60 for tomato was assumed. In addition, Cumulative Radiation Interception Maxima Product (CRIMP) values were also calculated by multiplying seasonal cumulative radiation values by the maximum observed interception of radiation based on the LAI_{max} values shown in Table 7-1.

Results and Discussion

Yield Characteristics

An overview of the yield characteristics for tomato is presented in Fig. 7-1. Depending on plant vigor and planting density the number of branches may range from 20 to 40 per plant, whereas up to 60 to 80 flower clusters may form (Fig. 7-1a). Semi-

Table 7-1. Overview of crop and yield characteristics for field-grown tomato at Bradenton in 1994 and 1995; Gainesville in1995 and 1996; Immokalee in 1995; and Quincy in 1995.

Treatment	LAI_{max}	Branch	Fruit cluster	Total fruit yield			Marketable fruit yield				DM%
		(no plant^{-1})	(no plant^{-1})	t ha^{-1}	no plant^{-1}	g fruit^{-1}	t ha^{-1}	(%)	no plant^{-1}	g fruit^{-1}	
Brad. '94											
N-Exp.											
N=180	4.87	41.5	67.5	125.0	151.0	74.6	106.2	85.0	59.5	160.8	6.21
N=258	6.00	38.0	59.5	147.1	141.0	94.0	132.4	90.0	70.0	170.4	5.72
N=336	5.88	34.0	70.5	153.9	140.5	98.7	146.2	95.0	73.5	179.2	6.03
Brad. '95											
N-Exp.											
N= 0	0.82	14.0	21.0	22.8	22.0	93.4	13.9	61.0	9.3	134.7	6.06
N=100	2.48	30.0	51.0	70.7	61.4	123.1	53.3	75.0	34.7	138.3	5.37
N=200	3.19	36.7	69.0	77.3	67.7	102.9	65.0	84.1	50.3	116.4	5.45
N=300	3.47	42.0	72.3	71.1	67.3	95.2	58.4	82.1	44.3	118.8	5.28
Exp. 2	3.12	37.5	80.0	97.2	65.5	133.6	91.7	94.3	42.5	193.1	5.89
Fall crop	5.25	65.0	91.0	76.7	105.5	65.5	46.0	60.0	24.0	174.2	5.89
G'ville '95											
Hochmuth	3.37	20.0	43.0	107.5	27.0	215.0	102.7	95.5	21.0	264.4	5.26
G'ville '96											
N-Exp.											
N= 0	0.60	18.0	24.5	22.9	11.5	161.9	21.1	92.1	8.5	203.6	5.43
N=133	2.07	20.5	38.5	64.2	36.5	143.0	53.0	82.6	24.0	168.8	4.87
N=200	2.36	20.0	38.0	65.2	43.0	123.3	59.9	91.9	27.0	183.1	4.78
N=266	2.41	20.0	40.0	79.1	38.0	169.2	69.0	87.2	27.0	207.0	4.75
N=333	2.68	21.5	46.0	77.5	39.0	161.6	64.9	83.8	33.0	160.5	5.14
Irrigation Exp.											
CB1	1.69	23.0	38.0	65.7	36.0	148.4	57.2	87.1	30.3	153.4	5.10
CB2	1.96	32.7	36.7	54.7	42.3	105.1	41.1	77.0	24.0	142.6	5.71
CB3	2.59	31.3	43.0	63.3	48.3	106.6	50.2	79.2	29.3	139.3	5.78
Control	2.63	33.0	44.0	84.5	53.7	128.0	74.3	87.9	39.7	152.2	5.36
Imm. '95											
Spring crop	1.54	20.5	37.3	53.3	39.5	112.4	38.2	71.7	27.5	115.8	4.93
Fall crop	4.24	39.5	49.5	78.4	53.5	122.1	67.9	86.6	34.5	164.0	5.01
Quincy '95											
Spring crop	2.99	32.7	58.7	78.1	64.7	132.8	74.0	94.8	47.0	173.2	4.51
N-Exp.											
N= 0	0.92	22.0	37.3	21.0	20.7	84.5	15.4	73.4	10.7	119.9	4.67
N= 66	2.38	31.3	46.3	43.5	31.7	114.4	36.0	82.8	19.0	157.9	4.79
N=133	2.39	35.3	54.0	48.1	41.3	97.1	33.5	69.6	20.0	139.6	4.64
N=200	2.94	36.7	53.3	66.4	47.0	117.7	52.6	79.2	28.3	154.9	4.91
N=266	2.66	40.0	54.3	54.1	50.7	88.9	40.0	73.9	26.0	128.2	4.80

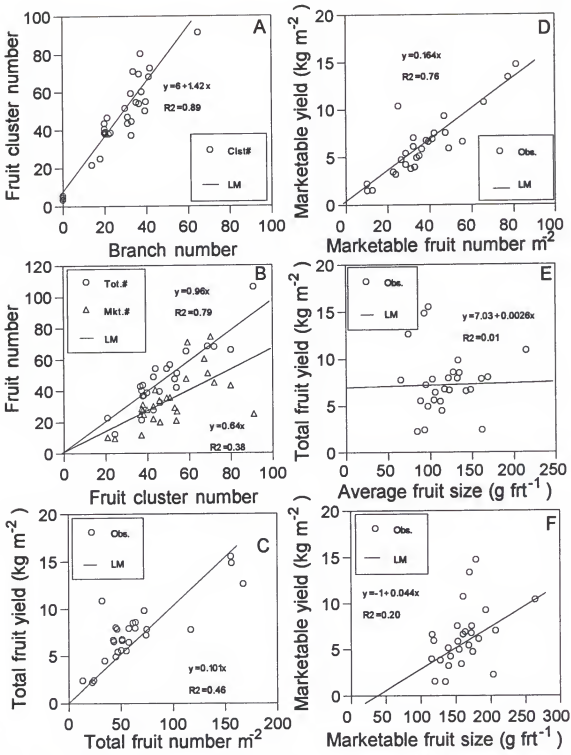


Fig. 7-1. Graphic overview of yield characteristics for tomato at all locations outlined in Table 7-1, plotting a) fruit cluster number against branch number; b) fruit number against fruit cluster number; c) total fruit yield against total fruit number; d) marketable fruit yield against marketable fruit number; e) total fruit yield against average fruit size; and f) marketable yield against average fruit size.

determinate tomato plants typically form about four fruit clusters per branch. Theoretically, plants thus have the capacity to form as many as 160 fruit clusters. However, many lateral shoots may not (fully) develop, resulting in an overall branch-to-fruit-cluster ratio of 1 to 1.4 (Fig. 7-1a). The number of fruits formed per plant depends on the total number of fruit clusters and the fruit-set percentage of these clusters. Based on the data shown in Fig. 7-1b, it may be concluded that only one fruit forms per fruit cluster and that only two thirds of all fruits formed will reach marketable fruit size (> 57 mm). However, the number of flowers formed per fruit cluster for commercial varieties ranges from 4 to 12 (Varga and Bruinsma, 1986). Measured flower numbers per fruit cluster number were 5.5, 5.0, and 4.1 for fruit clusters located on the main stem, and on first- and second-order laterals, respectively. Based on such results the overall fruit set would be on the order of only 20%, which appears to be low. Effects of fruit cluster position on fruit-set percentage for the Bradenton 1994 season are shown in Fig. 7-2. Fruit number formed per fruit cluster, and fruit-set percentage, decreased with fruit cluster number and also as the order of branching increased. First-formed clusters thus may have up to 4 fruits and a fruit-set percentage of around 70%. Reported values for flower number per fruit cluster, and fruit-set percentage for field-grown tomato at other locations, were 4.3 and 70.0%, respectively (Nassar, 1986; Scholberg, 1987; Wien and Minotti, 1987). Prolonged periods with relatively low radiation and high temperatures (conditions that sometimes prevail during the latter part of the growing season in Florida) may reduce fruit set appreciably (Gosselin et al., 1988).

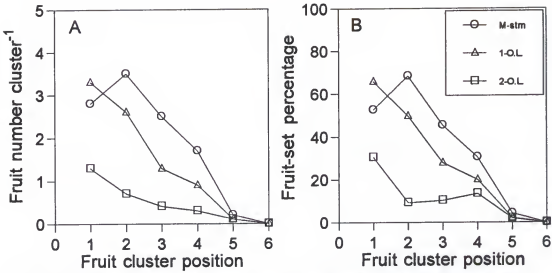


Fig. 7-2. Effect of fruit-cluster position on a) fruit number formed per cluster; and b) fruit-set percentage for the 1994 growing season at Bradenton.

Based on the slopes of Figs. 7-1c and 7-1d, it may be concluded that average fruit weights for total and marketable fruits were on the order of 101 and 164 grams, respectively. However, under optimal conditions, average fruit size for most commercial varieties is typically around 200 g frt^{-1} (Csizinszky and Schuster 1982; Rhoads et al., 1988; Wien and Minotti, 1987). Total fruit yield was unaffected by average fruit size (Fig. 7-1e), while differences in marketable fruit yield were more strongly affected by changes in fruit numbers than by changes in fruit size. Similar results were reported by Vinten et al. (1986).

Although average fruit size appears to be a fairly stable and genetically controlled production trait, actual marketable fruit size and fruit size-distribution may still be affected by both management practices and environmental conditions. An overview of fruit size distribution for a number of locations is presented in Table 7-2. Fruits larger than 57 mm typically accounted for 88% of the total fruit yield, and 69% of the total fruit number.

Table 7-2. Overview of size distribution for tomato fruit weight and fruit numbers at Bradenton in 1994 and 1995; Gainesville in 1995 and 1996; Immokalee in 1995; and Quincy in 1995.

Treatment	Fraction of total fruit weight					Fraction of total fruit number				
	Small	Medium	Large	Extra Large	Marketable	Small	Medium	Large	Extra Large	Marketable
Bradenton 1994										
Avg.	0.10	0.19	0.39	0.31	0.90	0.40	0.18	0.27	0.15	0.60
Bradenton 1995										
N= 0	0.28	0.45	0.12	0.15	0.72	0.52	0.36	0.07	0.06	0.48
N=100	0.25	0.44	0.21	0.11	0.75	0.35	0.39	0.21	0.06	0.65
N=200	0.17	0.35	0.41	0.07	0.83	0.32	0.35	0.30	0.04	0.68
N=300	0.14	0.27	0.41	0.17	0.86	0.33	0.27	0.31	0.09	0.67
Gainesville 1995										
Hochmuth	0.05	0.05	0.12	0.78	0.95	--	--	--	--	--
Gainesville 1996										
N-Exp.										
N= 0	0.08	0.17	0.09	0.66	0.92	0.29	0.21	0.08	0.42	0.71
N=133	0.10	0.32	0.26	0.32	0.90	0.20	0.38	0.24	0.18	0.80
N=200	0.08	0.12	0.20	0.60	0.92	0.23	0.19	0.20	0.39	0.77
N=266	0.11	0.15	0.10	0.64	0.89	0.28	0.21	0.11	0.40	0.72
N=333	0.12	0.30	0.20	0.38	0.88	0.28	0.36	0.16	0.20	0.72
Irrigation Exp.										
CB1	0.09	0.29	0.35	0.27	0.91	0.24	0.35	0.23	0.18	0.76
CB2	0.17	0.24	0.24	0.35	0.83	0.39	0.27	0.19	0.15	0.61
CB3	0.19	0.38	0.15	0.27	0.81	0.38	0.36	0.11	0.14	0.62
Control	0.16	0.25	0.22	0.37	0.84	0.25	0.26	0.29	0.20	0.75
Immokalee 1995										
Fall crop	0.13	0.30	0.15	0.41	0.87	0.36	0.21	0.32	0.11	0.64
Quincy 1995										
Spring crop	0.06	0.17	0.28	0.49	0.94	0.26	0.19	0.24	0.31	0.74
Av. non-limiting conditions	0.12	0.21	0.25	0.42	0.88	0.31	0.23	0.28	0.18	0.69
Csizinszky and Schuster, 1982	0.04	0.21	0.43	0.32	0.96	0.09	0.28	0.43	0.21	0.91
Everett, 1976	0.14	0.36	0.34	0.15	0.85	--	--	--	--	--
Hochmuth et al., 1989	0.06	0.10	0.27	0.57	0.94	--	--	--	--	--

The relatively high marketable-fruit number reported by Csizinszky and Schuster (1982) could be related to the sampling criteria. During growth studies all fruits (> 10 mm) were measured, whereas for most field experiments this would be unfeasible, and typically only fruits larger than 48 to 57 mm are harvested. For well-managed crops, half of the total fruit number and roughly 75 to 95% of the total fruit weight fall within the large and extra-large size fractions.

For Gainesville during the 1996 growing season, excessively high N rates prolonged the vegetative growth cycle, resulting in high numbers of relatively small fruits near the end of the growing season. However, the fraction of large and extra-large fruits in the total fruit yield increased as N-rates increased. Effects of N-stress on fruit distribution therefore may vary between locations and growing seasons, similar to trends reported by Everett (1976). Severe N-stress and water-stress during initial growth resulted in stunted plants, with fewer fruits and flower clusters (Table 7-1). Vegetative growth ceased 2-3 weeks earlier compared to well-fertilized plants, and flowers on newly formed fruit clusters typically aborted shortly after anthesis. However, fruit ripening typically occurred 5-10 days earlier then for well-watered and well-fertilized plots. N-stress and irrigation cutback treatments resulted in an appreciable decrease in fruit yield (Table 7-1), with average fruit sizes for these treatments being either similar to or higher than for other treatments. Ample supply of both water and N, on the other hand, favored both fruit-set and fruit formation during the latter part of the growing season.

Under typical Florida conditions, high humidity and temperatures during mid-summer may result in rapid canopy decline during the maturation of last-formed fruits.

The resulting decline in assimilate supply, along with increased exposure of these fruits to both direct sunlight and diseases, often results in smaller and poorer quality fruits. Inadequate N supply during the second part of the growing season, on the other hand, may cause premature crop senescence and increased yield losses due to "sunburn" of the fruits. Excessive pruning of lateral branches was reported to cause similar problems (Olson, 1989). Irregular irrigation water supply and nutritional imbalances may cause physiological disorders and increased yield losses due to blossom-end rot and fruit cracking (Doorenbos and Kassam, 1986). Under such conditions, the percentage marketable fruit may be well below the values outlined above. For modeling purposes, a value between 0.85 and 0.95 appears to be realistic to convert total fruit yield into marketable fruit yield. However, this value depends on marketing standards, with values for specific production systems being specified in the experimental detail (TMX) file of CROPGRO.

Effects of Fruit Size on Fruit Weight

Results of the application of Equation 1 to fruits collected during the 1995 growing season for Bradenton, Gainesville, and Quincy are shown in Fig. 7-3. Fruiting coefficients ranged from 1.01 to 1.11, depending on fruit characteristics. Once the value of FC was determined, the model fitted the data surprisingly well. Specific values for FC may vary between cultivars, and probably should be included as an input parameter in the cultivar (CUL) file of CROPGRO. For modeling purposes, a fixed value for FC between 0.95 and 1.05 may be assumed. Alternatively, a simple program may be included that

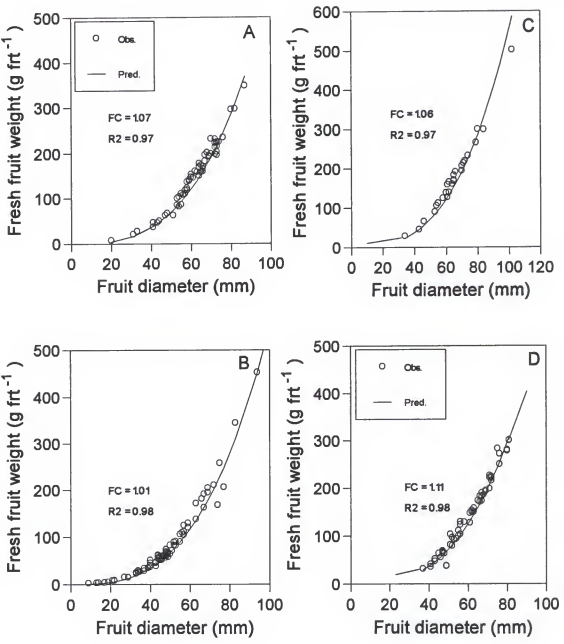


Fig. 7-3. Fruit size plotted as a function of fruit diameter for a) Bradenton 1995; b) Gainesville 1995; c) Gainesville 1995 (data of G.J. Hochmuth); d) and Quincy 1995. Fruit fresh weight was predicted by using fitted fruiting coefficient (FC) values from equation 1.

would calculate a specific FC value for approximately 20 fruits based on input values entered in the experimental details file. With the model used here, fruit-size characteristics can be captured in a single coefficient, which appears to be desirable. The use of Equation 1 also facilitates the conversion of fresh fruit weights into size categories, which is required to predict marketable fruit weight (most commercial production systems base fruit quality for tomato on fruit size). The use of fruit size to define fruit development seems to be appropriate, since it allows a simple and continuous description of fruit properties expressed in what can be coined as "radial time". The results of the tagged-fruit experiments, which will be presented below, provided further information on the conversion of thermal to radial units, since both were measured in real time.

Fruit Development

Effects of irrigation and zero-N treatments on the development of tomato fruit are shown in Fig. 7-4. Six weeks after anthesis, average fruit diameter ranged from 64 mm for the zero-N treatment to 72 mm for the control, with intermediate values for the irrigation cutback treatments (Fig. 7-5a). During initial fruit development, plants of the second irrigation cutback treatment (CB2) showed mid-day wilting, and water uptake by these fruit during initial growth may also have been affected. Fruit diameters for the CB1 treatment thus may have been lower compared to the relatively well-adjusted plants of the first irrigation-cutback treatment (CB1).

Tomato fruit fresh or dry weight plotted against time resulted in expolinear growth patterns. After an initial lag-period of approximately one week, fruits showed an almost

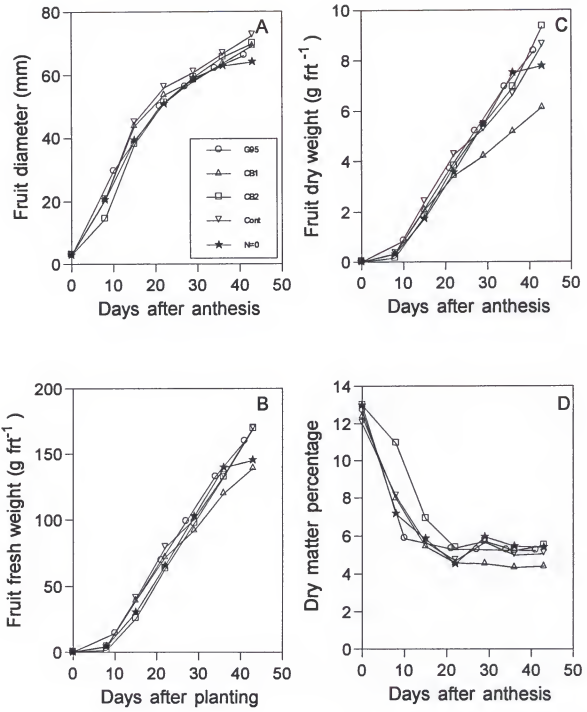


Fig. 7-4. Effects of irrigation treatments [irrigation cut-off at 2 weeks (CB1) and 5 weeks (CB2) after transplanting] and N-rate [0 (N=0) vs 202 kg N ha $^{-1}$(control)] on a) fruit diameter; b) fruit fresh weight; c) fruit dry weight; and d) dry matter percentage of tomato fruits for the 1995 (control only) and 1996 growing seasons at Gainesville.

linear increase (linear growth phase) of both fresh fruit weight and dry matter over time (Figs. 7-4b and 7-4c). This linear increase in fruit fresh weight and dry matter was also observed for greenhouse tomato and, under favorable growing conditions, it may continue until fruits have attained nearly 90% of their final volume (Varga and Bruinsma, 1986). Six weeks after anthesis, fruit dry weight ranged between 6 and 9 grams per fruit, and average fresh fruit weights were on the order 140 to 170 grams. This compares favorably with values for greenhouse tomato (Ho et al., 1983; Varga and Bruinsma, 1986). N-stress resulted in an earlier deviation from this linear growth pattern, with similar results having been reported for salinity stress (Ehret and Ho, 1986).

The effects of water stress on fruit growth appear to be more complex. Although early-season fresh-fruit weights were typically higher for the CB1 treatment compared to the CB2 treatment (Fig. 7-4b), the reverse was true for late-season fruit dry weights (Fig. 7-4c). The dry matter percentage (DMP) for the CB1 treatments was also comparable to that of the CB2 treatment (Fig. 7-4d). The dry matter content of fruits for the CB1 and CB2 irrigation treatment decreased from approximately 12.4 and 13.0% at anthesis to 4.4 and 5.5%, respectively. The DMP of the fruit appeared to follow an exponential decay function, which is in agreement with observations by Ehret and Ho (1986). The sudden decrease in the DMP at day 21 could have been related to the 60 mm of rainfall that occurred two days earlier. Heavy rainfall (especially in water-stressed plants) is often reported to result in a sharp increase in water uptake and may even result in fruit cracking.

Absolute growth rates for tomato fruits were generally highest from 10 to 25 days after anthesis, and daily increments in fresh and dry weights were on the order of 5 and

0.3 g per day, respectively (Fig 7-5a to b). Corresponding values for greenhouse tomato were 3 and 0.20-0.27 g per day, respectively (Ho et al., 1987; Jones et al., 1989b). Lower values for greenhouse tomato could be related to relatively smaller fruit size for greenhouse tomato fruits (100 g compared to 180 g). The relative growth rate for tomato fruits showed a decrease with time (Fig. 7-5c to d), with similar results being reported for greenhouse tomato (Varga and Bruinsma, 1986). The peak in relative growth rate typically observed during the first week is indicative of the intense growth activity associated with cell division which occurs during initial fruit growth. In most cases, this rapid increase in fruit growth rate cannot be detected from plots of cumulative growth, since it occurs during the initial lag-phase (Varga and Bruinsma, 1986)

Seed Characteristics

Effects of the irrigation, zero-N, and control treatments on seed weights and seed fraction are shown in Table 7-3 and in Fig. 7-6. N-stress resulted in a reduction in both, whereas water stress resulted in a reduction in seed weight but an increase in seed

Table 7-3. Overview of relationships between seed weight and total fruit weight on a fresh-weight and dry-weight basis, along with average seed weights and dry matter content of the seeds, for Gainesville 1996.

	Fresh-weight basis				Dry -weight basis					
	Lin. equation	r^2	seed wt	pulp[1]	Lin. equation	r^2	seed wt	DMP		seed[2]
Trtm.			(mg sd^{-1})	fract.			(mg sd^{-1})	pulp	seed	fract.
Control	y= -0.93 + 0.013 x	0.81	11.1	0.983	y = - 0.34 + 0.086 x	0.72	4.7	5.60	41.9	0.052
CB1	y= -0.87 + 0.013 x	0.87	8.6	0.983	y = - 0.22 + 0.119 x	0.82	3.7	3.40	43.6	0.103
N=0	y= 0.01 + 0.005 x	0.58	7.5	0.990	y = - 0.05 + 0.055 x	0.89	2.9	4.08	39.6	0.050

[1] calculated value assuming a fresh fruit weight of 200g
[2] calculated value assuming a dry fruit weight of 10 g

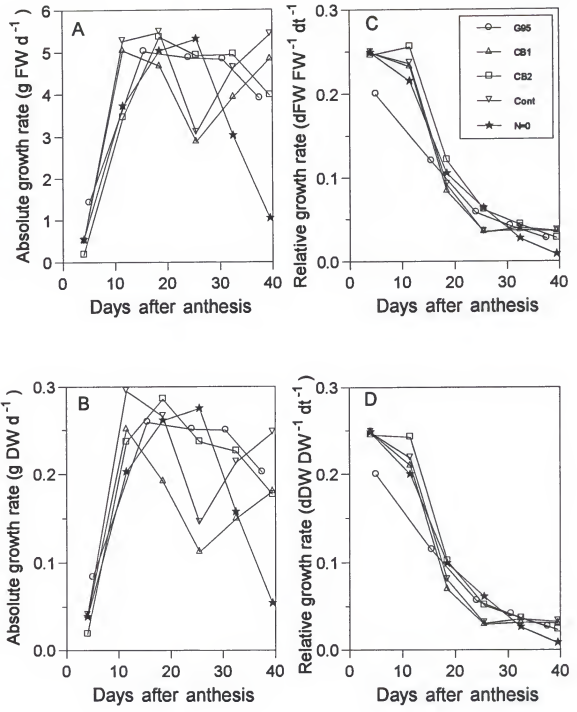


Fig. 7-5. Effects of irrigation treatments [irrigation cut-off at 2 weeks (CB1) and 5 weeks (CB2) after transplanting [and N-rate [0 (N=0) vs 202 kg N ha^{-1} (control)] on a) absolute growth rate (fruit fresh weight); b) absolute growth rate (fruit dry weight); c) relative growth rate (fruit fresh weight); and d) relative growth rate (fruit dry weight); for the 1995 (control only) and 1996 growing seasons in Gainesville.

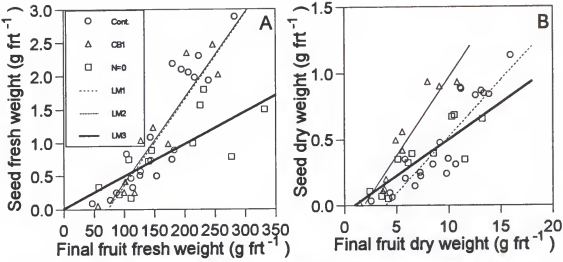


Fig. 7-6. Effects of irrigation treatments [irrigation cut-offs at 2 weeks (CB1) and 5 weeks (CB2) after transplanting] and N-rate [0 (N=0) vs 202 kg N ha^{-1} (control)] for Gainesville on a) seed fresh weight plotted against final fruit fresh weight; and b) seed dry weight plotted against final fruit dry weight. Linear relationships (LM1-3) are outlined in Table 7-3.

fraction. Average seed weights for the control and zero-N treatments were 4.7 and 2.9 mg sd^{-1}, respectively. Seed weight on a fresh- and dry-weight basis typically accounted for less than 2% and between 5 and 10% of total fruit weight, respectively. This difference is most likely related to the high dry matter content of the seed (40 to 44%) compared to that of the fruit pulp (3.4 to 5.6%).

Typically, tomato fruits contain 180 to 230 seeds, and final fruit weight was reported to be largely determined by seed number. In the absence of seeds, fruit growth is both delayed and reduced, with maximum fruit size of parthenocarpic fruits typically not exceeding 30 to 40 g (Varga and Bruinsma, 1986). Although fruit weight appeared to be controlled by seed number for both the irrigation and control treatments (control: FW = 75 + 0.85 seed no, r^2= 0.84; CB1: FW= 55 + 0.82 seed no, r^2 = 0.83), this relationship was less obvious for the N treatment, possibly due to increased variability in seed size.

Regressing seed dry weights upon final fruit dry weight, on the other hand, resulted in consistently high R-squared values. It should be noted that, in most cases, the y-intercept was significantly different from zero. The seed-to-final-fruit ratio is therefore not constant, but increases from 0.0 to 0.052 as fruit dry weight increases from 4 to 10 g.

Dynamics of Fruit Dry Matter Content

The decrease in dry matter percentage (DMP) of tomato fruits as a function of fruit diameter for Bradenton, Gainesville, and Quincy is shown in Fig. 7-7. Although variability of values may be partly related to differences in growing conditions between locations, the overall fit of the model appears to be satisfactory. Model coefficients are shown in Table 7-4.

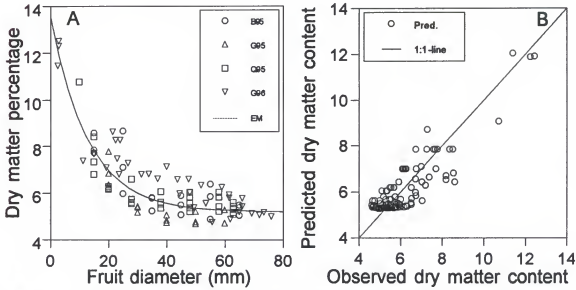


Fig. 7-7. a) Dry matter percentage of tomato fruits plotted as a function of fruit diameter; and b) predicted dry matter content plotted as a functon of observed dry matter content; for Bradenton 1995; Gainesville 1995; Quincy 1995; and Gainesville 1996. The exponential model (EM) expresses dry matter percentage as a function of fruit radius (equation 2), with model coefficients as presented in Table 7-4.

Table 7-4. Overview of dry matter percentage and fruit coefficients from equation 2 for Gainesville 1995 and 1996, Bradenton 1995, and Quincy 1995. Data for greenhouse tomato were obtained from Bussieres (1993)

Experiment	DMP_{min}	DMP_{max}	α	β	FC	r^2
Combined data	5.25	13.64	8.35	3.13	1.06	0.79
Gainesville '95	5.21	13.92	9.71	3.64	1.06	0.97
Gainesville '96						
CB1	3.66	13.39	9.73	1.64	0.93	0.96
CB2	4.16	14.17	10.01	1.31	0.94	0.94
N=0	5.23	14.30	9.07	3.07	1.00	0.90
Control	4.54	13.01	8.47	1.66	0.90	0.95
Bussieres, 1993	5.32	13.86	8.54	2.29	0.95	0.96

Results of fitted parameters in Equation 2 for tagged fruits at Gainesville 1995 and 1996, along with a data set obtained from the literature, are shown in Fig. 7-8. Overall R-squared values were relatively high compared to the combined data set, and the general model appeared to fit most data sets surprisingly well. It appeared that parameterization for the combined data set was similar to that for most of the other data sets. Even though values of β appear to be most prone to fluctuations, an assumed value around 3 appears to be appropriate under most conditions. The values of DMP_{max} appeared to be relatively constant compared to the relative changes in DMP_{min}. Similar results were reported for the effects of salinity on the DMP of tomato irrigated with saline water (Ehret and Ho, 1986). It thus may be necessary to define functional relationships that describe the effects of growth stress and source-sink relationships on the value of DMP_{min}.

Sink strength appears to be one of the key factors that controls dry matter accumulation by the fruit. However, Ehret and Ho (1986) reported that sink strength was only slightly affected by growth stress. As a result, dry matter accumulation by tomato

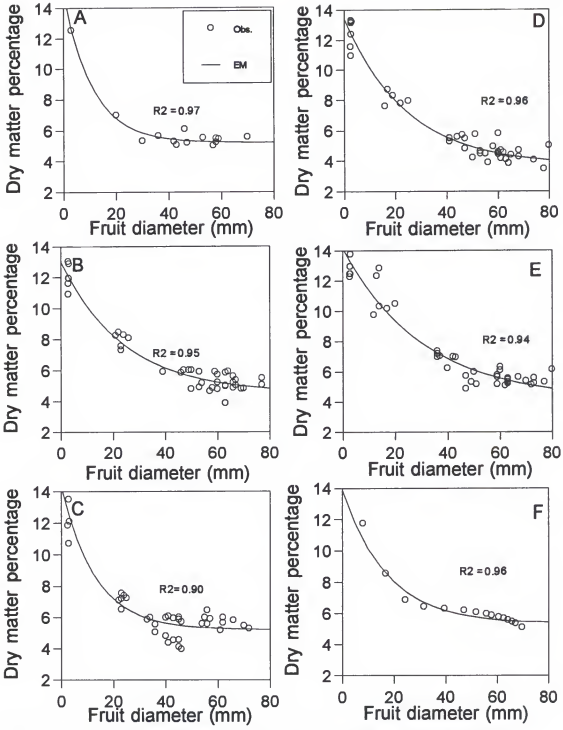


Fig. 7-8. Dry matter percentage of tomato fruits for a) Gainesville 1995 (control only); for the Gainesville 1996 b) control, c) zero N-rate, d) irrigation cut-off at 2 weeks (CB1) and e) irrigation cut-off at 5 weeks (CB2) treatments; and f) experimental data for greenhouse tomato (Bussieres, 1993). Exponential models (EM) express dry matter percentage (y) as a function of fruit diameter (x), with model coefficients as presented in Table 7-4.

fruits appears to be relatively unaffected by unfavorable growing conditions and, once a fruit is formed, it appears to grow at a relatively constant rate (Ho, 1988). If assimilate supply to the fruits is decreased due to unfavorable growing conditions, total assimilate demand by the fruits may exceed the total supply of assimilate by the canopy. In this case newly formed flowers and fruits will abort, and the fruit-set percentage may drop from approximately 80% to less than 30% (Bertin and Gary, 1993). Ho (1988) suggested that radiation levels during crop development may be the main environmental factor that controls dry matter content of the fruit. High solute concentrations, on the other hand, may also result in an appreciable increase in DMP of the fruit (Ehret and Ho, 1986). Increased N supply may result in a reduction in DMP, due to increased plant growth and a dilution of dry matter content of the fruit. However, at very high solute concentrations, a decrease in water uptake and a concurrent increase in DMP may occur due to increased osmotic stress. With an increase of N rate from 60 to 400 kg ha^{-1}, DMP of tomato fruit reportedly decreased from 5.41% to 5.25% (May and Gonzales, 1994). Huett and Dettmann (1988) reported that, with an increase in solution concentrations from 14 to 70 ppm N, DMP decreased from 5.8 to 5.4%. However, at still higher N concentrations, DMP increased again to a value of 5.9 %.

Temperature should affect both fruit development and duration of the growth period (Koning, 1989a). Plots of fruit radius as a function of thermal time are shown in Fig. 7-9, with regression relationships for specific treatments as shown in Table 7-5. The time required for fruit development and maturation for greenhouse tomato ranges from 54 to 65 days (Koning, 1989b). Wolf et al. (1986) reported that processing tomato

require about 31 and 59 physiological days for maximum fruit size and complete ripening, respectively. The corresponding values for fresh-market tomato would be on the order of 35 (Table 7-5) and 42 to 45 physiological days (assuming that fruit ripening may take 7 to 10 days under optimal conditions). Using the guidelines outlined in Appendix A, Table3,

Table 7-5. Overview of relationships between accumulated degree days after anthesis (dd) and fruit diameter; thermal time Cd($DIAM_{max}$); and physiological days to maximum fruit diameter for Gainesville 1995 and 1996.

Experiment	Quadratic equation	Cd ($DIAM_{max}$) (° Cd)	Physiol.[2] days	r^2
Gainesville '95	Diam = 3.8 + 0.173 dd - 0.000121 dd^2	713.2	39.6	1.00
Gainesville '96				
CB1	Diam = 2.2 + 0.186 dd - 0.000134 dd^2	696.9	38.7	0.99
CB2	Diam = 0.0 + 0.174 dd - 0.001062 dd^2	818.9	45.5	0.99
N=0	Diam = 1.5 + 0.183 dd - 0.000134 dd^2	682.2	37.9	0.98
Control	Diam = 2.0 + 0.192 dd - 0.000135 dd^2	712.1	39.6	0.99
Control (comb)	Diam = 3.1+ 0.181 dd - 0.000125 dd^2	721.9	40.1	0.98
Small fruits	Diam = 5.2 + 0.141 dd - 0.000129 dd^2	547.4	30.4	0.97

[1]Assuming that maximum fruit development occurs at 28 °C (Jones et al., 1989b)

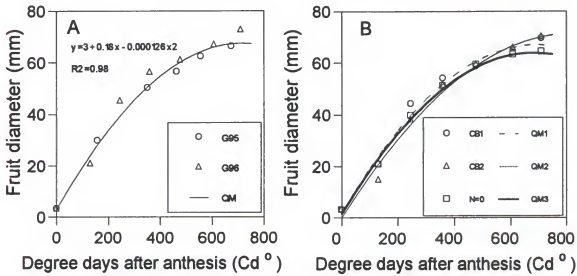


Fig. 7-9. Fruit diameter plotted against degree days for a) the control at Gainesville 1995 and 1996; and b) the irrigation [irrigation cut-off at 2 weeks (CB1) and 5 weeks (CB2) after transplanting] and zero -N treatments. The quadratic model (QM) expresses fruit diameter (y) as a function of degree days (x), with regression equations for specific treatments (Fig. 7-7b) as outlined in Table 7-5.

the number of days to maturation for fruits was calculated for fruits at 42 days after anthesis. Based on color evaluation of these fruits, calculated values were 5.6, 9.3, 10.0, and 3.5 for the CB1, CB2, control, and zero-N treatments. Similar results were observed by Wolf et al. (1986), who reported that water stress shortened the period of fruit growth by 2 to 3 days while the length of the ripening period was reduced by 4 to 5 days .

The reduction in DMP observed for the first irrigation cutback treatment is at variance with the increase in dry matter percentage of the fruit which is commonly observed for water-stressed plants (Borin, 1990; Lacheene and El-Beltagy, 1986; Perniola et al., 1994). However, since water stress occurred during initial plant growth, it also resulted in reduction of canopy development. This could have resulted in a reduction in assimilate supply to the fruit. Later during the growing season, water supply was resumed (through the depletion of soil moisture at greater soil depths and/or via rainfall), which could have resulted in a sharp decrease in DMP of the fruit. Ho (1988) reported that higher DMP of the fruit was correlated with greater leaf area per fruit. Results of linear regression analysis on effects of the LAI to Fruit Weight Ratio (LFWR) on DMP of fruits for the irrigation study in Gainesville are shown in Table 7-6. It appears that DMP of the fruit increased as the LFWR values increased, with most of the variability in DMP of the fruits for the irrigation trial being attributable to differences in LFWR values. Results of regression analysis for the N studies were inconclusive, since trends were less clear and also often inconsistent. Alternatively, the use of intercepted radiation during the fruit-filling period to predict dry matter percentage resulted in relatively low R-squared values (Table 7-6). It appears that, although irradiance may control the potential DMP of the

Table 7-6. Overview of relationships between the dry matter percentage of fruits and the LAI to fruit weight ratio (LFWR)[1] for irrigation study Gainesville 1996

	Linear equation	r^2
Absolute DMP-values	DMP = 3.76 + 5.62 LFWR[1]	0.95
	DMP = 3.85 + 0.003 RADabs[2]	0.28
Relative DMP-values[3]	DMPrel = 0.65 + 0.97 LFWR	0.95

[1] Expressed as m^2 leaf area [kg fruit weight]$^{-1}$
[2] Intercepted radiation during the period six weeks prior to harvesting based on equation 4
[3] DMPrel = DMP/DMP_{max}

fruit for a given production period (Ho, 1988), other factors such as water supply and internal source-sink regulations may also have an appreciable effect on actual DMP of the fruit.

To show some possible applications of the general concepts outlined above, fruit diameters for fruits collected at Gainesville were used to predict fruit weight (according to Equation 1). Equations 2 and 3 then were used to predict DMP and fruit dry weights (Figs. 7-10a to b). Predicted versus observed values are shown in Figs. 7-10c to d. Based on these initial results, it may be concluded that the proposed model appears to perform well. Based on the information provided in Table 7-7, fruit dry weights or fresh weights could then be used to partition fruit weights within cohorts to the size categories shown in Fig. 7-10. It may be desirable to also include stochastic components in the model to describe fruit size distribution within the same cohort, since reported dry matter accumulation for proximal fruits is higher than that for distal fruits (Ho et al., 1983).

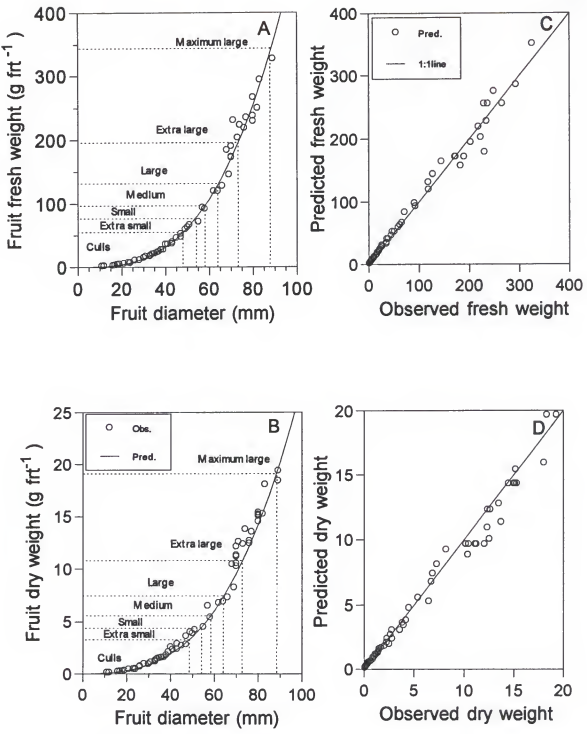


Fig. 7-10. Fruit diameter for Gainesville 1996 data plotted against a) fresh fruit weight and b) dry fruit weight; c) predicted fresh weights plotted against observed values; and d) predicted fruit dry weights plotted against observed values. Size classifications for tomato fruits were based on United States Department of Agriculture (1984) criteria as outlined in Table 7-7.

Table 7-7. Overview of upper and lower limits of fruit fresh weight, and fruit dry weight for range of fruit coefficients. Values based on USDA size designations.

Fruit size (mm)	Fresh weight ($g\ frt^{-1}$) Fruit coefficient.						Dry weight ($g\ frt^{-1}$) Fruit coefficient				
	0.90	0.95	1.00	1.05	1.10		0.90	0.95	1.00	1.05	1.10
						Culls					
48 ----------	52	55	58	61	64	-----	2.86	3.02	3.18	3.34	3.50 --
						Extra small					
54 ----------	73	78	83	87	91	-----	4.02	4.25	4.47	4.69	4.92 --
						Small					
58 ----------	92	97	102	107	112	-----	4.95	5.23	5.50	5.78	6.05 --
						Medium					
64 ----------	124	130	137	144	151	-----	6.61	6.97	7.34	7.71	8.07 --
						Large					
73 ----------	183	194	204	214	224	-----	9.76	10.3	10.8	11.4	11.9 --
						Extra large					
88 ----------	321	339	357	375	393	-----	17.0	18.0	18.9	19.8	20.8 --
						Max. large					

Effects of Radiation on Fruit Yield

Total fruit yield and fruit dry matter production appeared to be closely related to amount of radiation intercepted by the crop six weeks prior to harvest (Fig. 7-10a to b). Cumulative Radiation Interception Maxima Product (CRIMP) values were calculated by multiplying the cumulative radiation for the entire growing season [Equation 4] by the LAI_{max} values outlined in Table 7-1. Even though CRIMP values may not have a direct physical interpretation as do Radiation Use Efficiency (RUE) values, they still appear to be useful. They accounted for 86% of the variability in tomato yields for a range of production conditions. It was somewhat surprising that R-squared values for fruit dry matter yield were consistently lower than those for total yield. Neither the use of CRIMP

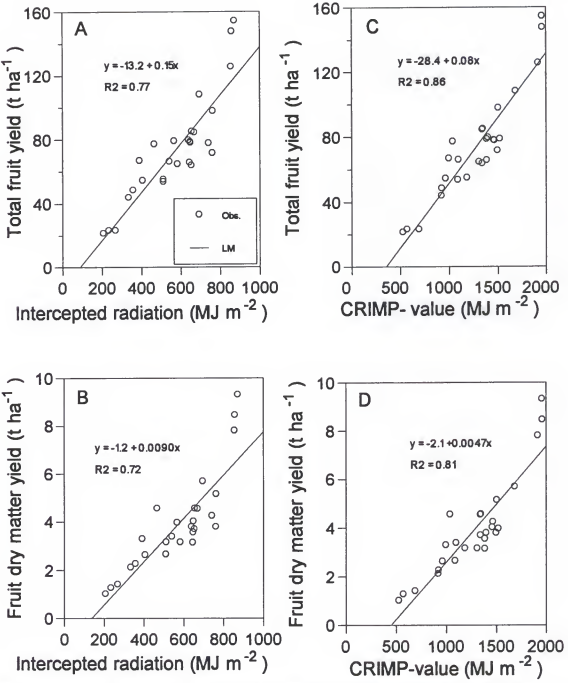


Fig. 7-11. Effects of cumulative radiation and radiation interception on a) total fruit yield plotted against intercepted radiation during the six weeks prior to harvesting; b) fruit dry matter yield plotted against intercepted radiation during the six weeks prior to harvesting; c) total fresh fruit yield plotted against the Cumulative Radiation Interception Maxima Product (CRIMP) value; and d) fruit dry matter yield plotted against the CRIMP-value; Linear relations show fruit yield (y) as a function of intercepted radiation and/or CRIMP-value (x) for the locations outlined in Table 7-1.

values nor intercepted radiation values appeared to be very useful in the prediction of DMC. For the experiments listed in Table 7-1, only 23% of the variation in observed DMC of tomato fruits was accounted for by either model.

Conclusions

Based on the discussion above, tomato plants may form up to 60 branches and therefore could produce as many as 240 fruit clusters and up to 1000 fruits per plant. The actual capacity of tomato plants to produce reproductive sites may be related to the growing conditions at their original gene center. This original growing environment may have favored selection of plants that could tolerate prolonged stress and that displayed adequate flexibility in fruiting patterns to still reproduce under such conditions.

Although the proposed model for prediction of DMC of tomato fruits is still in its initial developmental stages, preliminary modeling results appear to be promising. The model in its current form is simple and somewhat similar to the one proposed by Kenig et al. (1993). These authors used an empirical (exponential) model with three coefficients to predict the pod DMC of soybean as a function of reproductive growth stage. It is interesting to note that pod DMC for soybean was observed to increase over time due to the drying of pods during seed maturation. For tomato, on the other hand, the reverse is true. Since reproductive stages are ill-defined for a crop like tomato, it could be concluded that fruit diameter may be a more appropriate parameter with which to quantify fruit development. The model proposed here is also more mechanistic, since β, DMP_{min}, and DMP_{max} each have physiological significance. These coefficients actually describe the

dilution of dry matter as fruit growth shifts from cell division (during initial growth) to cell elongation during the latter half of fruit development.

Dry matter content of the fruit can also be defined as a function of fruit dry weight (results not shown) and resulting relations could also function in connection with the CROPGRO model. The CROPGRO model would calculate the dry matter accumulation by the fruit and, based on this dry weight the fruit diameter could be estimated (in a similar fashion as the results shown in Table 7-7). The fruit diameter can then be used to predict fruit fresh weight.

It can also be concluded that CRIMP values may be useful during initial assessment of yield potential for tomato in a specific production environment for which cumulative radiation and a LAI_{max} value are known or can be estimated. CRIMP values could also be used to evaluate the performance of more complex prediction models such as CROPGRO by comparing MSEP values for the two models in a similar fashion as was outlined in Chapter 3.

CHAPTER 8
ADAPTATION OF THE TOMGRO MODEL FOR FIELD-GROWN TOMATO

Introduction

During the 1980's, workers in Florida, Israel and France developed a tomato growth model (TOMGRO) for indeterminate greenhouse tomato (Jones et al., 1989ab, 1991b; Dayan et al., 1993). This model has been validated at a number of locations world-wide, suggesting that it is fairly "robust" for greenhouse settings (Bertin and Gary, 1993; Dayan et al., 1993; Koning, 1993). The time-course development of plant organs by the model is based on genetic plant properties, with plant growth assumed to be governed by temperature, solar radiation, and CO_2 concentration (Dayan et al, 1993). Partitioning among plant components is based on specific sink strength and availability of assimilates. Plant growth is represented by seven state variables: node, leaf and fruit number; dry weights of stems, leaves, and fruit; and areas of leaves. Plant growth is assumed to occur through changes in number, weight and areas of plant organs in each age class of each component (Jones et al., 1991b).

Growth characteristics of tomato are governed both by genetic traits and specific management practices (McNeal et al, 1995; Rick, 1978). Indeterminate plants typically form three leaf nodes between fruit clusters (Fig. 8-1), the formation of main-stem nodes continues throughout the growing season, and side branches are continually removed .

Fruit production is confined to a single main-stem, which may be coiled near the plant's base as growth continues for what may be as much as a 200-day growing season (McNeal et al., 1995). For field-grown tomato, on the other hand, fruit clusters alternate with two leaf nodes, node formation is terminated after the formation of 4-5 fruit clusters (Fig. 8-1), and only limited (early-season) control of branching is effected.

Tomatoes are grown on nearly 8,000 ha in Florida, and comprise nearly one-third of the total farm-crop value for the state's vegetables (McNeal et al., 1995). However, increased competition with other production regions along with more stringent environmental regulations may jeopardize future production. The use of expert systems should assist producers with more efficient use of natural resources and could also be used for the rapid initial evaluation of alternative management strategies. Expert systems were previously developed for other crops (e.g., the DSSAT system for field crops) and production systems (greenhouse settings), but none of these are directly applicable to field-grown tomato (Boote et al., 1989; Hoogeboom et al., 1992; Jones et al., 1989a).

Fig 8-1. Growth characteristics of semi-determinate and indeterminate cultivars (adapted from Rick, 1978; no lateral shoots are shown for the semi-determinate cultivar).

The primary objectives of this chapter are to: (a) describe differences in growth characteristics between indeterminate and determinate tomato varieties; (b) outline modifications necessary when adapting the TOMGRO model for field-grown tomato; (c) compare TOMGRO-predicted values with actual field measurements; (d) discuss limitations of the TOMGRO-predicted values based on actual growth analysis; and (e) show the effect of changes in some of the key growth parameters on predicted growth.

Materials and Method

Experiments involving the commercial cultivar "Sunny" (Lycopersicon esculentum Mill.) were conducted during the spring production seasons of 1991, 1992, and 1994 at the Gulf Coast Research and Education Center (REC) in Bradenton. The soil series at the research site was an Eaugallie fine sand (sandy, siliceous, hyperthermic, Alfic Haplaquods). The 1991 experiment was transplanted March 17 (Julian date 76), with transplants typically 25-30 days old, having 4-5 nodes, an initial leaf area of about 15 cm^2, and a dry weight of 0.2-0.25 g. Representative plants from the guard rows of a well-fertilized, well-watered (subirrigated) trial were sampled approximately biweekly. The 1992 and 1994 experiments were transplanted March 3 (Julian date 63) and March 1 (Julian date 60), respectively. During the 1992 growing season, the nitrogen (N) fertilization rate was approximately 180 kg ha^{-1}. Plant growth appeared to be less vigorous than for more heavily fertilized treatments by season's end, though yield of single-pick marketable (first-pick) tomatoes was statistically indistinguishable from those for more-heavily fertilized treatments in the same study. During the 1994 growing season, N rates

ranged from 160 to approximately 300 kg ha^{-1}. However, differences in plant growth for fertilizer treatments were statistically nonsignificant and, therefore, the average values for all treatments were combined.

A total of four (1991 and 1992) or six (1994) plants were sampled destructively on each sampling date, with non-destructive counts of main-stem and total nodes; numbers of leaves, flowers and fruit; and numbers of aborted leaves and flowers made during the intervening weeks as well. After measuring plant height and width and removal of support strings, plants were severed at ground height. Main-stem nodes then were counted as an index to plant-growth stage, leaves were counted, and leaf blades were separated from leaf petioles and from stem material. A representative subsample (approx. 1000-1500 cm^2) was run through a leaf-area meter on-site to permit assessment of whole-plant leaf area index, and both the leaf subsample and the remaining subcomponent samples (blades, petioles, stems and fruits) were dried at 65°C prior to dry-weight determinations followed by grinding and nutrient analysis.

Weather data were collected from an on-site weather station. Daily maximum and minimum temperatures, and incident radiation along with the geographical location of the experimental site, were entered into the TOMGRO weather file (FILE1). Plant density and row spacing, along with initial leaf weight and leaf area, were entered into the crop management file (MGT.TOM). No water or nutrient-supply subroutine is included in TOMGRO as currently constituted. A number of growth parameters listed in the input file (CROPPARM.TOM) were modified subsequently to better describe the growth of field-

grown tomato. An overview of these changes is presented in Appendix C, Tables 1 through 3.

Results and Discussion

Specific Growth Characteristics of Field-Grown Tomato

Due to the removal of lateral shoots, leaf area development of greenhouse crops typically remains sink-limited for a longer period, resulting in a slower initial rate of canopy development compared to a field crop (Fig. 8-2). However, the number of fruits formed appears to be similar for both types of crops (Fig. 8-3). The total number of fruits formed is thus not determined by the total number of flower clusters formed but rather by assimilate supply and fruit set (Varga and Bruinsma, 1986). This appears to be in agreement with commonly observed poor fruit set for the upper fruit clusters and the fruit clusters of higher-order branches of field-grown tomato (Fig. 7-2). Most fruits formed on higher-order laterals are initiated only after the formation of 22-27 nodes (or after 56-70 days), and may not reach maturity. Later-formed fruits are often also of lower quality. The average fruit-set percentages of the first fruit cluster for main-stem and first- and second-order laterals for the 1994 growing season were 53%, 66% and 31%, respectively. Respective values for the fourth fruit cluster were 31%, 20%, and 13%. However, total fruit dry weight after the formation of 42 (total) nodes was on the order of 360 g m^{-2} for a greenhouse crop compared to 650-850 g m^{-2} for a field crop (Jones et al., 1989b; Scholberg, 1994). This is likely related to greater fruit size for field-grown varieties used

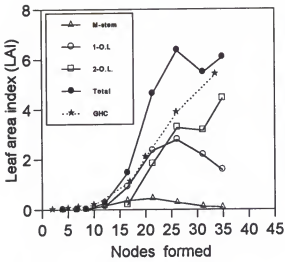


Fig 8-2. Canopy characteristics for field-grown tomato (Bradenton, 1994): leaf area of leaves formed on the mainstem (M-stem); first-order laterals (1-O.L.); higher order laterals (2-O.L.); and total leaf area (Total) in comparison with a greenhouse crop (GHC, data of Jones et al., 1991b).

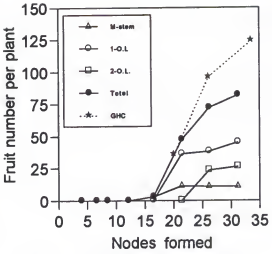


Fig 8-3. Fruiting characteristics for field-grown tomato (Bradenton, 1994): number of fruits formed on the mainstem (M-stem); first-order laterals (1-O.L.), higher- order laterals (2-O.L.); and total fruit number (Total) in comparison with a greenhouse crop (GHC, data of Jones et al., 1991b).

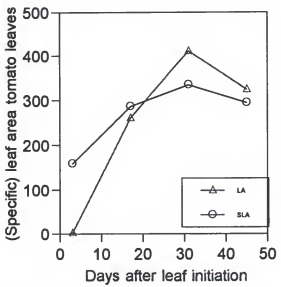


Fig 8-4. Time-course development of leaf area (cm^2 per leaf) and specific leaf area (cm^2 per gram) for field-grown tomato (Bradenton, 1994).

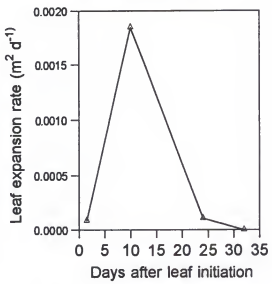


Fig 8-5. Leaf expansion rate for field-grown tomato (Bradenton, 1994)

in Florida (average fresh fruit weight for field-grown crops being on the order of 160-240 g $fruit^{-1}$ compared to 80-160 g $fruit^{-1}$ for most greenhouse crops).

The duration of leaf growth for field-grown tomato is on the order of 25-35 days, depending on the temperature. Development rates can thus be as high as 0.040 (Fig. 8-4). Maximum leaf size is on the order of 300-450 cm^2, which is about half of the values reported for greenhouse crops (Jones et al., 1989b). Leaf expansion rates for field cultivars and greenhouse cultivars are approximately 0.0018 (Fig. 8-5) and 0.0027 $m^2 d^{-1}$ (Jones et al., 1989b). Higher leaf expansion rates may be related to the higher specific leaf area (SLA) values commonly observed for greenhouse tomato. Typically, SLA for field-grown crops ranges from 180-200 $cm^2 g^{-1}$ during initial growth to 325-350 $cm^2 g^{-1}$ after leaf expansion has ceased. Leaf weight may still increase during secondary leaf thickening, whereas leaf size remains constant. This results in a decrease in SLA (Fig. 8-4).

The leaf area associated with main-stem leaves accounts for less than 10% of the total leaf area (Fig. 8-2), with the maximum leaf area being attained after formation of the terminal fruit cluster (which occurs at 18-20 nodes). The number of first-order laterals ranges from 5 to 11, the maximum area associated with them is attained at about 27 nodes, and they may account for up to 60% of the total leaf area. The leaf area associated with higher-order laterals may continue to increase after the formation of as many as 35 nodes depending on fruit load, plant vigor and the incidence of pests and diseases. The reduction in leaf area observed for main-stem and first-order lateral leaves is related to leaf aging, senescence, and shading of lower and/or innermost leaves. The staking and tying of field crops may also cause sudden changes in light distribution within the canopy (and

sometimes physical damage to branches), which in turn can result in increased leaf senescence. Values of LAI for a field crop range from 4.5-6.5, compared to LAI values of up to 7 or 8 for greenhouse crops (Jones et al., 1989b). Poor canopy development and/or rapid canopy senescence due to diseases may reduce the availability of assimilates for fruit growth, and can also reduce fruit quality due to sunburn. LAI typically decreases near the end of the growing season, due to increased reallocation of photosynthates to the fruit.

Growth Predictions Using TOMGRO

Simulation results for Bradenton 1991(without branching)

With use of the original version of the TOMGRO model, late-season main-stem node number for the 1991 growing season was over-predicted (Fig. 8-6a) while total leaf number (Fig. 8-6b), leaf area, and leaf weight (not shown) were under-predicted. For field cultivars, main-stem node formation ceases after initiation of the terminal fruit cluster, but first- and second-order lateral branches continue to form nodes. The original version of TOMGRO did not include a branching routine, and the model only predicted the number of main-stem leaves. Total leaf number, leaf area, and leaf weight thus were under-predicted.

To match TOMGRO-predicted growth to that observed for field cultivars, the look-up table of the CROPPARM.TOM file was modified by using a text editor without changing the FORTRAN 77 code. To suitably fit the field growth data, the GENRAT (number of nodes formed per day) parameter was increased from 0.5 nodes d^{-1} to 2.0 and

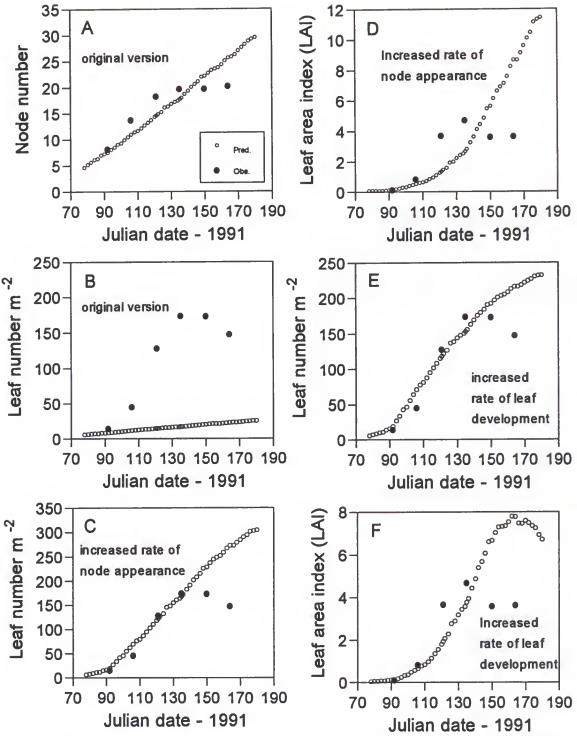


Fig. 8-6. TOMGRO-predicted (original version without branching) vs observed (Bradenton 1991) time-course changes in a) node number; b), c) and e) leaf number (without and with accelerated node formation and increased leaf development rates, respectively) and d) and f) leaf area index (for leaf development rates of 0.013 and 0.039, respectively).

10 nodes d^{-1} after the formation of 8 and 12 main-stem nodes, respectively (Appendix C, Table 2). These numbers reflect the total number of nodes being formed. To mimic the semi-determinate growth habit of the field cultivar, the GENRAT factor then was reduced to 1.0 nodes d^{-1} after the formation of 200 nodes. This overall approach resulted in more realistic prediction of early-season leaf numbers (Fig. 8-6c). However, early-season leaf area was still under-predicted (Fig. 8-6b), while late-season leaf number and leaf area were over-predicted.

To simulate more rapid canopy build-up, maximum leaf development rate (RDVLVT) next was increased from 0.013 to 0.039 (Appendix C, Table 2). This implies that maximum leaf size is attained after 25 days instead of 77 days. The increase in leaf-development rate resulted in a "tailing off" in the predicted leaf numbers and leaf area index (Figs. 8-6e and 8-6f). This is likely related to more rapid aging of the leaves and thus increased leaf senescence of lower leaves under field conditions, which appears to be realistic. Early-season predictions for leaf area increased, but mid-season values were still under-predicted. Late-season values were reduced appreciably but remained relatively high compared to actual values (Fig. 8-7). Subsequently, the rates of leaf expansion (POL) in the CROPPARM.TOM file were doubled in order to obtain a better fit of late-season leaf number (Fig. 8-7a) and early-season leaf area (Fig. 8-7b). However, this resulted in excessively high predicted values for late-season leaf area, whereas leaf dry weight was still under-predicted (Fig. 8-7c). In order to scale down predicted LAI values, values for the maximum, minimum, and standard specific leaf area (SLA) were also modified in the CROPPARM.TOM file. The new values of SLAMX, SLAMN, and STDSLA were

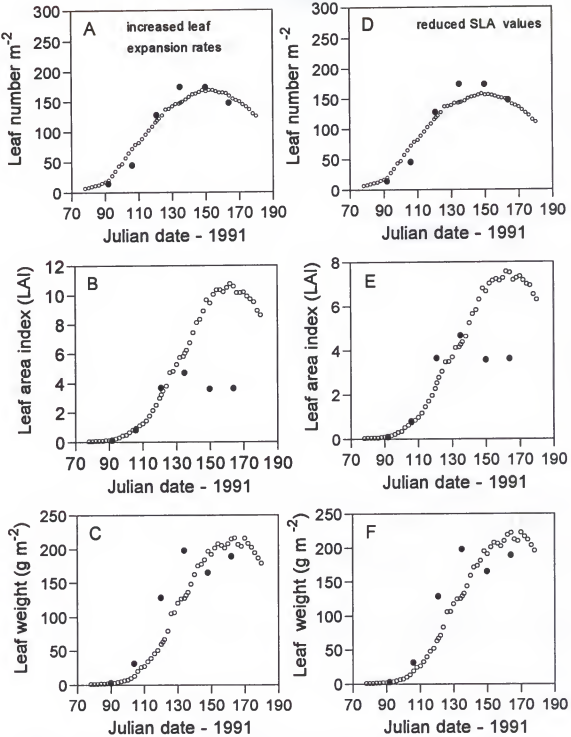


Fig. 8-7. TOMGRO-predicted (original version without branching) vs observed (Bradenton 1991) time-course changes in a) and d) leaf number; b) and e) leaf area index; and c) and f) leaf weight [with a-c reflecting increased leaf expansion rates, and d-f reflecting reduced specific leaf area values].

assumed to be 0.040, 0.020, and 0.034 $m^2 d^{-1}$, respectively (Appendix C, Table 2). These changes had little effect on TOMGRO-predicted leaf number and leaf weight, but reduced late-season LAI values by roughly 30%. Further decreases in the SLA value resulted in delayed canopy build-up and an overall poor fit of field data. The predicted onset of fruit production occurred too late, with both fruit number and fruit weight being greatly under-predicted (data not shown).

Simulation results for Bradenton 1991(with branching)

To incorporate branching, and to mimic the growth characteristics typical of field-grown tomato, it was necessary to change the model's FORTRAN 77 code (J. W. Jones, unpublished TOMGRO program revision). Two new parameters were included in the CROPPARM.TOM file: NBR (node position at which the first lateral shoot appears) and BRMX (the maximum number of branches that are formed). Based on experimental observations, values of NBR and BRMAX were set to 1 and 60, respectively (Appendix C, Table 3). An additional parameter (CLSDMF, the ratio of fruit growth to total assimilate demand for growth) was also included in the subroutine which calculates the rate of leaf development (DEVRATE.FOR). As a result, the rate of leaf appearance was reduced as the fruit number increased.

Effects of changing values of BRMX from 0 to 60 on leaf number are shown in Figs. 8-8a and 8-8b. Activating the branching routine was effective in more accurately predicting the number of leaves that form without changing the standard rate of node appearance (Appendix C, Table 3). However, predicted leaf area development was still

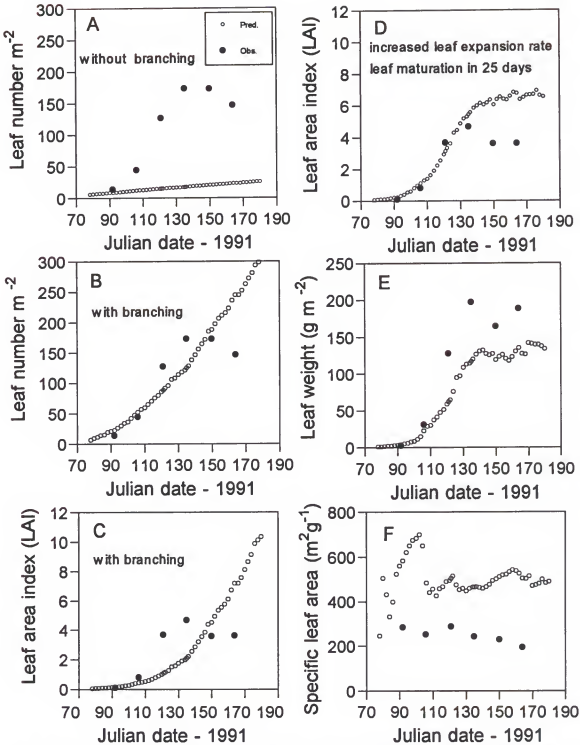


Fig. 8-8. TOMGRO-predicted (modified version simulating branching) vs observed (Bradenton 1991) time-course changes in a) and b) leaf number; c) and d) leaf area index; e) leaf weight; and f) specific leaf area [with "a" reflecting deactivated branching routine; b-c reflecting original crop parameters; and d-f reflecting increased leaf expansion and leaf development rates].

too low and, thus, the rates of leaf development and leaf expansion were increased as outlined above. This resulted in a better early-season fit of both leaf area and leaf weight (Figs. 8-8d and 8-8e). However, late-season leaf area was over-predicted while leaf weight was under-predicted. The model apparently over-predicted SLA values (Fig. 8-8f). This was remedied by modifying SLA values as outlined above. Based on experimental data the petiole fraction was also reduced from 0.49 to 0.33, with the effects of this parameter's changes being shown in Fig. 8-9. Overall predicted values of leaf number and leaf area index matched observed data fairly closely (Figs. 8-9a and 8-9b). However, late-season LAI values were over-predicted, whereas leaf weights were under-predicted. Predicted values of SLA appeared to be within the same range as the observed values, even though the predicted values were still too high. Further reduction in SLA values resulted in an overall poorer fit (except for SLA) of all observed parameters (data not shown).

The prediction of fruit production appeared to be not greatly improved by incorporation of the branching routine. Both the onset of fruit production (Fig. 8-9e) and total fruit production per plant (Fig. 8-9f) were under-predicted. Examination of the fruit number curve revealed that the onset of fruit production was not correctly predicted by the model. Based on the slope of this curve, it was also concluded that fruit number towards the end of the growing season increased too rapidly. It should be noted that the fruit number further appeared to increase in a step-wise fashion, which may not be realistic. The increase of total fruit weight over time appears to be too slow. In addition to a timing effect, this may be related to limited sink capacity of the fruit and to limited assimilate supply. Based on actual growth patterns for field cultivars (Fig. 8-1), the value

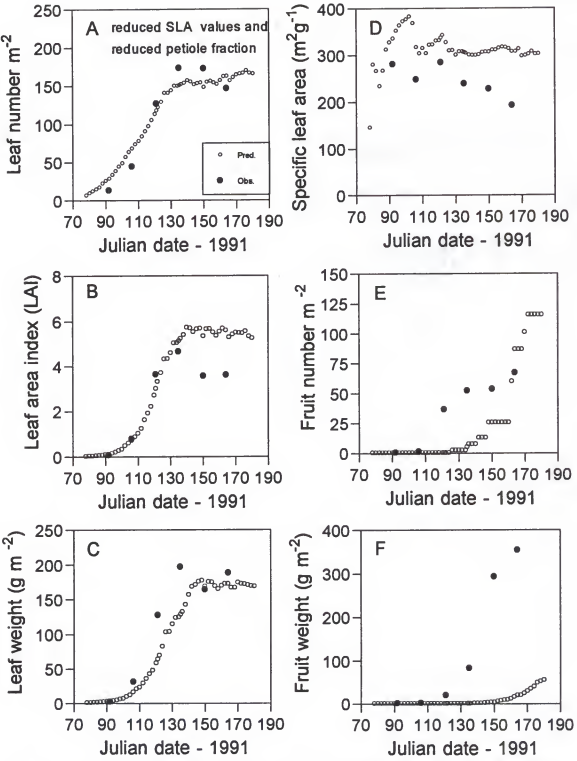


Fig. 8-9. TOMGRO-predicted (modified version simulating branching) vs observed (Bradenton 1991) time-course changes in a) leaf number; b) leaf area index; c) leaf weight; d) specific leaf area; e) fruit number; and f) fruit weight [a-f reflecting reduced sla values, and a petiole fraction of 0.33].

of the TPL parameter (the number of trusses per number of leaves) was increased from 0.33 to 0.5 (Appendix C, Table 3). In addition, the value of FTRUSN (the node position where the first truss appears) was reduced from 12 to 6, and the sink strength of the fruits was increased by 33% to account for the larger fruit size of field cultivars. Based on the fruiting characteristics of field-grown tomato, the number of fruits formed at the upper clusters was reduced, and fruit formation beyond the twentieth cluster was set to zero (Appendix C, Table 3).

The above changes in fruit-development parameters resulted in a decrease in leaf number (Fig. 8-10a), a slight delay in canopy development (Figs. 8-10b and 8-10c), and a slight reduction in SLA values (Fig. 7-10d). The decrease in leaf number appears to be related to the reduced proportion of leaves to fruits (this ratio had been decreased from 3:1 to 2:1) and the earlier initiation of fruit clusters (previously all stem nodes below the thirteenth node were assumed to be leaf nodes). Based on this, the number of fruit clusters formed for the first twenty stem nodes was increased from 2 to 6, resulting in a reduction in leaf number by 20%. Although predicted fruit initiation started earlier, the simulated onset of fruit production was still about 3 weeks too late (Fig. 7-10e and 7-10f). Earlier fruit initiation, along with increased sink strength, resulted in an increase in fruit yields by about 30%. However, final fruit dry yield was only on the order of 100 g $plant^{-1}$, which is only a fraction of actual fruit yields (up to 350-700 g $plant^{-1}$). Reducing the value of FTRUSN further and/or increasing the sink strength of the fruit resulted in only small increases in predicted fruit weight, but also resulted in a further delay of canopy

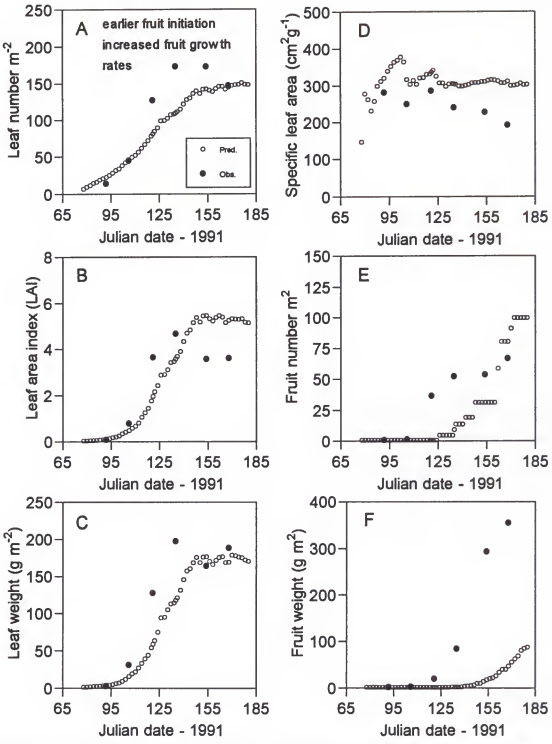


Fig 8-10. TOMGRO-predicted (modified version simulating branching, more rapid leaf development, reduced SLA values, reduced petiole fraction, earlier fruit initiation, and increased fruit growth rates) vs observed (Bradenton 1991) time-course changes in a) leaf number; b) leaf area index; c) leaf weight; d) specific leaf area; e) fruit number; and f) fruit weight.

development (data not shown). It was decided to confirm these results via independent data sets, with results for the 1992 and 1994 growing season to be discussed below.

Simulation results for Bradenton 1992 (with branching)

Leaf number was over-predicted for most of the 1992 growing seasons (Fig. 8-11a), while leaf area and leaf weight closely matched observed values during initial growth (Fig. 8-11b and Fig. 8-11c). However, both leaf area and leaf weight were over-predicted during the latter part of the growing season, and values of SLA were over-predicted during most of the growing season. The predicted onset of fruit production for the 1992 growing season appeared to match observed values more closely than in 1991 (Figs. 8-11e and 8-10e). Although the predicted fruit number was over-predicted, the simulated values of fruit dry weight were actually under-predicted, with the slope of the predicted line being only one third that of the observed data points. The rate of TOMGRO-calculated assimilate supply to the fruit appears to be only a fraction of that for field cultivars.

The observed "lag" in actual leaf area development between days 100 and 130 (Fig. 8-11b) could be related to water stress. A resumption of rapid growth after day 130 seemed to support this hypothesis (with resumed plant growth commonly being observed after temporary water stress). However, it should be noted that effects of both water and nutrient stress on plant growth are not simulated by TOMGRO at present.

Overall growth characteristics for the 1992 growing season were different than those observed in 1991 (Figs. 8-10 and 8-11). The 1992 crop was planted two weeks earlier, which resulted in slower initial crop development. In addition, plant spacing was

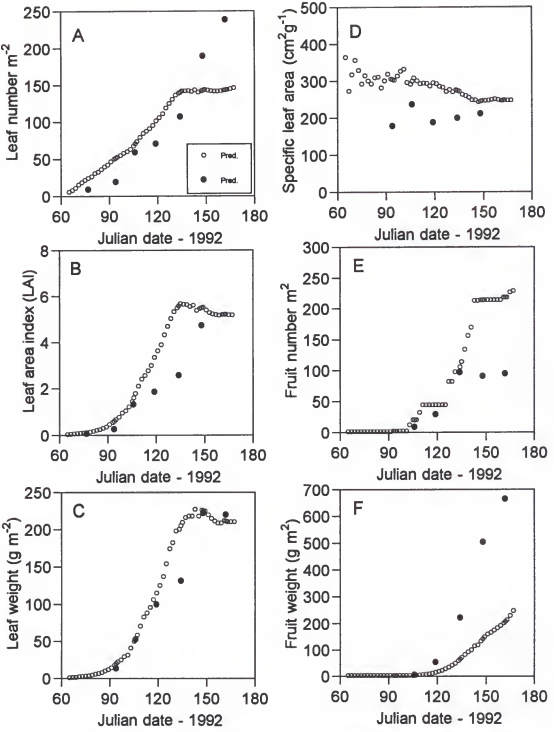


Fig 8-11. TOMGRO-predicted (modified version simulating branching, more rapid leaf development, reduced SLA values, reduced petiole fraction, earlier fruit initiation, and increased fruit growth rates) vs observed (Bradenton 1992) time-course changes in a) leaf number; b) leaf area index; c) leaf weight; d) specific leaf area; e) fruit number; and f) fruit weight.

reduced, resulting in greater leaf numbers per m^2. Canopy development was slower in 1992 (Fig. 8-11), however, which may have been related to lower temperatures during initial crop development and the slightly lower N-fertilization rates (McNeal et al., 1995).

Simulation results for Bradenton 1994 (with branching)

Leaf number for the 1994 growing season was slightly over-predicted during the initial part of the growing season, and greatly under-predicted during the rest of the growing season (Fig. 8-12a). However, observed leaf numbers appeared to be high compared to other production seasons (Marlowe et al., 1983; McNeal et al., 1995). Predicted values for both leaf area and initial leaf weight matched observed values closely, but late-season leaf weight was under-predicted (Figs. 8-12b and 8-12c). Simulated SLA values matched actual values fairly closely. It is unclear what causes the difference in SLA values between growing seasons. It is possible that the high fertilizer rates used during the first experiment resulted in an increase in SLA during initial growth. Predicted fruit number for the 1994 growing season matched actual fruit number fairly closely (Fig. 8-12e), but actual fruit weight was greatly under-predicted (Fig. 8-12f).

Validation results of the TOMGRO model for greenhouse crops appeared to give much more satisfactory results for predicted fruit yield than those reported here (Bertin and Gary, 1993; Dayan et al., 1993). This seems to agree with the notion that TOMGRO-predicted sink-source dynamics do not adequately match those of field cultivars. Effects of source/sink ratio on fruit development, fruit abortion, and vegetative development are well-defined for greenhouse tomato (Dayan et al., 1993; Ho et al., 1987; Varga and

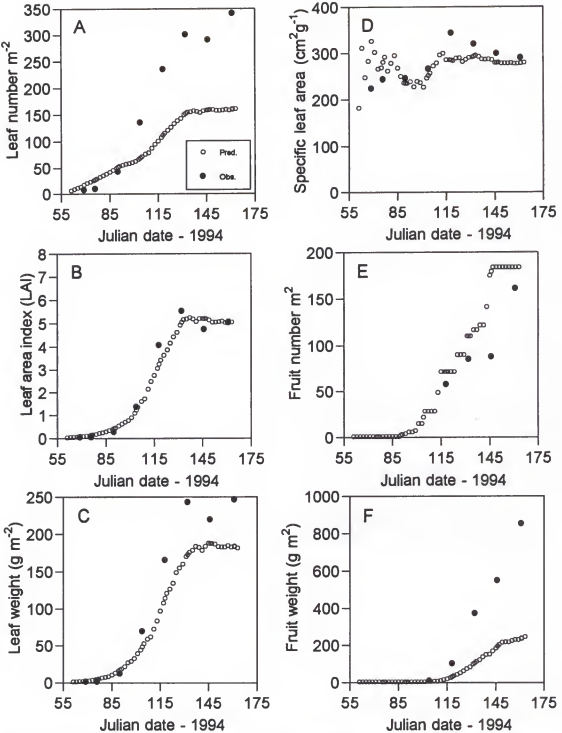


Fig 8-12. TOMGRO-predicted (modified version simulating branching, more rapid leaf development, reduced SLA values, reduced petiole fraction, earlier fruit initiation, and increased fruit growth rates) vs observed (Bradenton 1994) time-course changes in a) leaf number; b) leaf area index; c) leaf weight; d) specific leaf area ; e) fruit number; and f) fruit weight.

Bruinsma, 1986). However, little information is available on the time-course source/sink dynamics of field crops, and observed dynamics may also be greatly affected by variations in environmental conditions. Based on observations in the field, maximum rates of dry matter accumulation in fruits may range from 0.30 to 0.35 g d^{-1} $fruit^{-1}$, which is 10-30% higher than reported for greenhouse cultivars (Jones et al 1989b). It also appears that initial fruit development for greenhouse cultivars is slower than that for field cultivars, and that predicted fruit development for field cultivars may be source-limited.

Sensitivity Analysis

To show the effect of parameter modifications on modeling results, sensitivity analysis was conducted for the branching parameters (BRMAX, NBR), the specific leaf area parameters (SLAMX, STDSLA, and SLAMN), the leaf development-rate parameter (RDVLVT), and the leaf expansion rate (POL). During these analysis, the Bradenton 1991 data set was used and all other parameters, except for the one being tested, were held constant.

Increasing NBR (the node number at which initial branching occurs) from 1 to 10 resulted in an increase of the lag phase (Fig. 8-13a, run #1). Reducing BRMAX (the maximum number of lateral branches that are formed) from 60 to 5 did not affect initial leaf formation (Fig. 8-13a, run #2). However, it did result in a more rapid onset of the linear growth phase and a reduction in overall leaf number. It may be argued that the optimal value of NBR should be greater than one (since the initial fit was better for run #2). However, based on field observations, lateral shoots actually do form at the very first

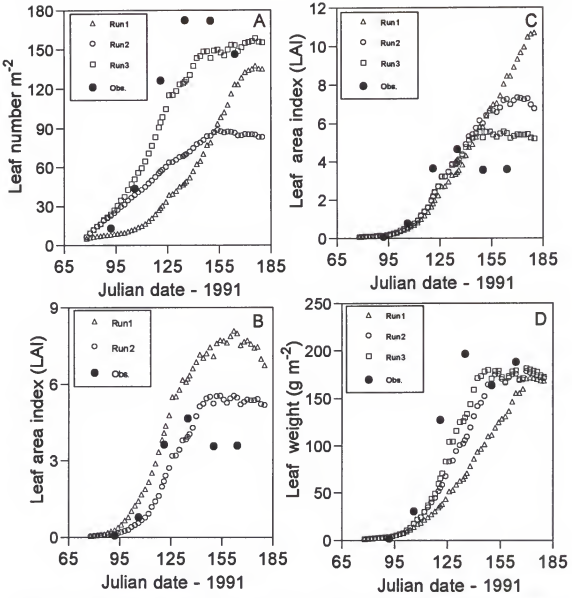


Fig. 8-13. Simulated effects of changes in a) maximum branch number (BRMAX) and branch initiation number (NBR) on leaf number [assumed branching parameters were: BRMAX=5 and NBR=10 for run 1; BRMAX=60 and NBR=10 for run 2; BRMAX=60 and NBR=1 for run 3] ; b) maximum (SLAMX), standard (STDSLA) and minimum (SLAMN) specific leaf area on leaf area index [run 1: SLAMX=0.75, STDSLA=0.75, SLAMN=0.20; run 2: SLAMX=0.40, STDSLA=0.34; SLAMN=0.20] ; c) leaf development rate on leaf area index [days to leaf maturation were 77, 38, and 26 days, for runs 1, 2, and 3, respectively]; and d) leaf expansion rate (POL) on leaf area index (c) and leaf weight (d) [maximum leaf expansion rates were 0.0015, 0.0029, and 0.0058 $m^2\ d^{-1}$ for runs 1, 2, and 3, respectively].

cluster. However, they may not develop subsequently until 6-10 nodes are formed. Including this lag phase in the model (similar to the lag phase for fruit development) may be more realistic but it should result in an under-prediction of leaf area development and may require further modification of the branching routine.

Reducing SLA values (original and modified values of SLAMX, STDSLA, and SLAMN were 0.75, 0.24, and 0.75; and 0.40, 0.20, and 0.34, respectively) resulted in slower build-up of leaf area (Fig. 8-13b). Lower SLA values (run #2) are indicative of thicker leaves, and the development of leaf area is thus delayed and total leaf area for a given total leaf weight is also reduced. It may be argued that relaxing the constraint on SLA values would result in a better early-season fit. However, SLA values are typically as low as 180 to 200 during initial plant growth. This is related to the low temperatures, high radiation levels, and high soluble salt concentrations commonly observed for subirrigated spring tomato crops in Florida.

Decreasing the number of days required for leaves to attain full leaf size from 77 days (Fig. 8-13c, run #1) to 38 days (Fig. 8-13c, run #2) resulted in slightly faster build-up of the leaf canopy. However, effects of this change on canopy aging are far more pronounced and it appears that a further reduction to 26 days (Fig. 8-13c, run #3) results in a growth pattern that matches observed growth patterns fairly closely. Modifying leaf expansion rate (POL) also appears to have a more pronounced effect on early-season canopy formation than modifying leaf development rates. It appears that reducing POL values by 50% (Fig. 8-13d, run #1) has a more pronounced effect on canopy development than doubling POL values (Fig. 8-13d, run #3). This seems to be in agreement with the

observations made for fruit expansion rates (POF) and it appears that, with increasing sink strength, the effects of source limitations become more obvious. Although the increase in leaf expansion appeared to improve model predictions, parameter values appeared to be inflated compared to those observed in the field (Fig. 8-5). After the change in fruit cluster initiation rate, late season leaf number was consistently under-predicted (Figs. 8-10a, 8-11a, and 8-12a). It may thus be more appropriate to increase leaf initation rate instead of increasing leaf area expansion rate. This appears to require further modification of the branching routine.

Conclusions

It may be concluded that ,after including a branching routine into TOMGRO, the model adequately described the vegetative growth patterns for field-grown tomato. However, the TOMGRO model was originally designed to describe the growth of single-stemmed greenhouse cultivars. These cultivars typically feature a relatively simple and constant growth pattern occurring on one hierarchical level of organization, but field cultivars appear to have more complex growth characteristics, and branching characteristics may result in a hierarchical structure with up to three levels of organization. Specific traits such as appearance of the first fruit cluster, leaf size, and fruit-set percentage appear to differ between different levels of organization, and also may be affected by factors not included in the model. As a result, a more empirical approach was followed in order to describe general plant growth under "optimal" growing conditions. However, since the effects of water and nutrient stress (which may occur under field

conditions) are not addressed by the TOMGRO model at present, the model can only be used to predict potential (vegetative) growth. The large discrepancy between actual and observed fruit yields further limited the usefulness of the TOMGRO model to predict fruit yields for field-grown tomato. As a result, it was decided instead to modify a more generic growth model that could address these issues.

CHAPTER 9
ADAPTATION OF THE CROPGRO MODEL FOR FIELD-GROWN TOMATO

Introduction

For the past few decades, researchers have developed dynamic crop-growth simulation models. These models are generally process-oriented and based on the flow of carbon, water, and nutrients within the soil-plant-atmosphere continuum (Hoogenboom et al., 1992). This allows the simulation of plant growth under well-defined environmental conditions (Jones and Ritchie 1992). Over time some of these models have evolved to fairly robust versions that can provide inputs to management decisions for commercial crops like peanut (Boote et al., 1989) and tomato (Jones et al., 1989a).

With establishment of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) during the 1980's, research efforts of a number of modeling groups were linked, resulting in the development of the Decision Support System for Agrotechnology Transfer (DSSAT) modeling package (Hoogenboom et al., 1992). A generic crop model (CROPGRO) included in this DSSAT package allows the simulation of plant growth over a wide range of field crops and production systems.

In recent years a number of models have been developed for tomato in order to predict harvesting date (Wolf et al. 1986), dry matter production (Koning, 1993), or the effect of CO_2 enrichment on plant production (Jones et al., 1989b). However, the use of

each model has been usually confined to a small group of researchers, and model application has been limited to either greenhouse or processing tomato.

The TOMGRO model (Jones et al., 1989a), a growth model developed for greenhouse tomato, was designed to respond to dynamically changing temperature, solar radiation, and CO_2 concentrations, assuming single-stemmed plants and no water or nutrient stress. The large number of photosynthetic and plant growth measurements used during its calibration resulted in a well-calibrated model for greenhouse tomato over a wide range of environmental conditions. However, McNeal et al., (1995) found that TOMGRO did not adequately describe the growth of field-grown tomato. Typically, node formation of field-grown tomato ceases after about twenty nodes whereas, for greenhouse tomato, node formation continues throughout the entire growth period (Scholberg 1994). The profuse branching typically observed for field crops also results in a more rapid buildup of leaf canopy mass, while the more deterministic growth pattern causes an earlier and more rapid decline of the leaf canopy. Similar plant-growth patterns have been observed for other field crops including peanut (Boote et al., 1986). It was thus hypothesized that it may be more appropriate to adapt an existing growth model for field crops to describe the growth of field-grown tomato, especially if that model could also account for the effects of both water and nutrient stress on plant growth. Since canopy development for field-grown tomato resembles that of peanut, modifying an existing crop model for peanut was considered to be a good starting point for the development of a tomato growth model. The CROPGRO model was chosen because of its generic nature and its wide use and acceptance in the modeling and agricultural-research communities.

User-friendly interfaces and graphics output, the use of standardized input files, the quality of its documentation, and the linkage of the growth routine to both water and nutrient balances also appeared to be useful features of the CROPGRO model (Hoogenboom et al., 1992). Such features should facilitate adaptation and testing of the CROPGRO model for field-grown tomato by scientists in other regions of the world. It was hypothesized that, if adaptation of the model could be realized for tomato without changing the overall structure of the CROPGRO model, then a similar approach might be used for other vegetable crops as well.

The primary objectives of this chapter are to: (1) outline some of the most important modifications to crop- and cultivar-specific parameters in order to model tomato plant growth; (2) show the importance of these parameters on simulation results through the use of sensitivity analysis; (3) present results of initial model calibration for data sets collected at the Gulf Coast REC in Bradenton during 1991, 1992, and 1994; (4) compare the canopy and the leaf-level photosynthesic routines for these data sets; and (5) present some general guidelines for further modifications of the CROPGRO crop model.

Materials and Methods

Data were collected from experiments conducted at the Gulf Coast Research and Education Center (GCREC) in Bradenton (FL) during the spring seasons of 1991, 1992, and 1994 on an Eaugallie fine sand (sandy, siliceous, hyperthermic, Alfic Haplaquods). Tomato (Lycopersicon esculentum Mill.) transplants (cv. Sunny) were planted on raised (fumigated) beds covered with black polyethylene mulch on 18 March, 3 March and 1

March of the respective years. Plant spacing was 1.5 by 0.6 m. and plants were subirrigated with drip-lines buried at a depth of 40 cm (termed locally the fully-enclosed seepage irrigation system). Plants were typically well-fertilized and no nutrient stress was observed, except for apparent N-stress near the end of the 1992 growing season at Bradenton. The incidence of pests and diseases was controlled by frequent applications of agrochemicals.

Plant growth measurements for representative plants (node number; plant height; dry weights of roots, stems, leaves, and fruits; and leaf area) were collected biweekly, with a compiled data set being entered into time-course data files (TMT files). All information pertinent to crop, fertilizer, and irrigation management was entered into experimental-detail files (TMX files) using the DSSAT V3 standardized format (Jones et al., 1994). Similarly, specific soil-profile descriptions for the experimental locations were added to the SOIL.SOL file of the DSSAT shell. Daily values of minimum and maximum temperature, solar radiation, and rainfall for both locations were placed in the weather data files (WTH files).

A systematic approach was used during the calibration process of the CROPGRO model for tomato. During initial modifications of crop-specific parameters, the phenological development coefficients were calibrated in order to match observed node development rate, date of flowering, fruit development, and fruit characteristics. An overview of the definition of these and other coefficients, with their respective values and units, is presented in Table 9-1. In order to calibrate the model for the cost of tissue

Table 9-1. Definitions of modified photosynthetic, phenological, vegetative, and reproductive coefficients with units and numeric values used in the TMGRO940 species- and cultivar-specific input files.

Parameter	Definition	Units	Value
Photosynthetic coefficients			
PAR	Photosynthetically active radiation	mol m^{-2} d^{-1}	--
PHT_{max}	Daily photosynthetic production capacity for a fully developed canopy intercepting all of the incident PAR at optimal temperature, leaf N concentration, and other conditions	g (CH_2O) m^{-2} d^{-1}	75.54
K_p	Empirical coefficient that defines the curvature of the exponential light response function	--	0.0386
K_{ext}	Light extinction coefficient	--	0.60
Phenological coefficients			
TRIFL	Rate of node appearance	nodes d^{-1}	0.52
VSSINK	Maximum node number to which plant remains sink-limited	--	4.0
Vegetative development coefficients			
SIZL	Maximum size of a fully expanded leaf	cm^2	300
SLAVAR	Specific leaf area of cultivar under standard optimum growing conditions	cm^2 g^{-1}	340
LFMAX	Light-saturated leaf photosynthesis rate at 30 ° C, 350 vpm CO_2, and high light	mg CO_2 m^{-2} s^{-1}	1.36
FRLFF	Fraction of daily increase in vegetative weight which goes to leaves during the "final" growth stage	--	0.30
FRSTMF	Fraction of daily increase in vegetative weight which goes to stems during the "final" growth stage	--	0.50
RTSEN	Fraction of root length that is senesced per physiological day		0.03
Reproductive coefficients			
THRSH	Maximum ratio of seed/(seed + shell) * 100	--	5.2
WTPSD	Maximum weight per seed	g	0.0035
SDPDV	Potential seed number per fruit	--	250
LNGSH	Time required for fruit growth	photothermal days	30
SD-PM	Time between first seed and physiological maturity	photothermal days	50
XFRT	Maximum fraction of daily growth that is partitioned to the fruit	--	0.77

Table 9-2. Maximum and minimum protein concentrations of root, stem, leaf blade, and fruit tissue for tomato during growth and after N-mining. Values were obtained from tissue analysis for the 1991 and 1994 experiments at Bradenton. Protein values were calculated by multiplying total-N concentrations by 6.25

	Plant tissue protein concentration		
	During growth		After
	Maximum	Minimum	N-mining
	(g protein per g tissue)		
Roots	0.144	0.119	0.060
Stem	0.256	0.156	0.112
Leaf Blade	0.370	0.220	0.154
Fruit	0.245	0.110	0.100

synthesis, plant composition values were entered using tissue analysis for tomato and/or values reported in the literature. Protein levels of tomato plant parts were derived from actual nitrogen concentrations of plant parts and are presented in Table 9-2. Subsequent steps included defining a look-up function for tomato seedling potential leaf area during the sink-limited development phase; characterizing specific leaf properties such as leaf size and specific leaf area (SLA); defining partitioning of assimilates to plant organs as a function of node number; and estimating values of photosynthetic parameters.

An expression that describes the instantaneous production of photosynthates (Pg) as a function of photosynthetic photon flux density (PPFD) and leaf area was developed by Acock et al. (1978). A modified version of this equation was developed by Jones et al. (1989a) to simulate canopy Pg for greenhouse tomato in the TOMGRO model:

$$P_g = \frac{D \cdot LF_{max}}{K} \ln\left(\frac{(1-m)\,LF_{max} + Q_e \cdot K \cdot PPFD}{(1-m)\,LF_{max} + Q_e \cdot K \cdot PPFD \cdot EXP(-K \cdot LAI)}\right) PGRED(T) \qquad (1)$$

where D = coefficient to convert P_g from μMol (CO_2) m^{-2} s^{-1} to g (CH_2O) m^{-2} h^{-1} ; K= light extinction coefficient; m = leaf light transmission coefficient; LF_{max} = maximum leaf photosynthetic rate (μMol m^{-2} s^{-1}); Q_e = leaf quantum efficiency (μMol CO_2 fixed μM $photon^{-1}$); PPFD = photosynthetic photon flux density (μMol m^{-2} s^{-1}); PGRED(T) = function to modify Pg under different daytime temperatures (°C); and LAI = canopy leaf area index. This model was used to simulate hourly values of Pg for days with different amounts of solar radiation. Hourly values of Pg were integrated to give total daily Pg. Since this model was well-calibrated for a wide range of environmental conditions, it was used to simulate Pg for a range of total daily photosynthetically active radiation (PAR) values from 0 to 54 mol m^{-2} d^{-1} for a tomato crop with an LAI of 5. These simulated daily Pg and solar radiation values were used to parameterize the simple equation in CROPGRO that relates daily canopy Pg to daily solar radiation. This equation is:

$$Pg_{max} = PHT_{max}(1 - e^{-K_p * PAR}) \qquad (2)$$

where Pg_{max} is the daily photosynthetic production capacity for a fully developed canopy intercepting all of the incident photosynthetically active radiation (PAR) at optimal temperature, N-tissue content, and other conditions. Non-linear regression analysis (SAS Institute, Cary, NC) was used to deduce the values for PHT_{max} (maximum photosynthetic production capacity under non-limiting conditions) and K_p (an empirical coefficient that defines the curvature of the exponential light response function). The fitted values of K_p and PHT_{max} were used in the TMGRO940.SPE file during the initial calibration of SLAVAR, XFRT, and K_{can}. Subsequently, the value of K_{can} was adjusted to fit simulated values to those observed in the field.

To show the effect of parameter modifications on modeling results, sensitivity analyses were conducted for K_p, PHT_{max}, K_{can}, FRSTMF, FRTFF, RTSEN, XFRT, and SLAVR, since each of these parameters had been shown to greatly affect modeling results during calibration. During these sensitivity analyses, the 1994 Bradenton data set was used and all parameters, except the one being tested, were held constant. Results were obtained by first increasing only PHT_{max} (from 61 to 75) and then subsequently increasing both PHT_{max} and K_p (from 0.025 to 0.040). Increments of $\pm$ 5-10% of the estimated value of the parameter were used for the other coefficients, resulting in steps of 0.10, 25, and 0.10 for K_{can}, SLAVR, and XFRT, respectively. Using the calibrated model, further simulations were made for the 1991 and 1992 growing seasons at Bradenton to evaluate overall fit of the calibrated model to the experimental data. This is not a validation of the model, however, since these data sets were also used during the calibration of the model. An overview of the TMGRO940.SPE, CUL, and ECO files on which modified parameters are designated is presented in Appendix D, Tables 1 through 3.

Results and Discussion

Model Adaptation

Photosynthesis

Fitting of the exponential photosynthetic function used by CROPGRO to the light-response curve generated by TOMGRO (Fig. 9-1, solid line) resulted in estimates for PHT_{max} and K_p of 75.54 and 0.0386, respectively. Using these values in Equation 2 resulted in the CROPGRO light-response curve for tomato (Fig. 9-1, dashed line). The

value of K_{can}, the light extinction coefficient, was reduced from 0.75 to 0.60. This new value was obtained by fitting simulated values of crop parameters to those measured in the field. The reduction in the value of K_{can} is related to the relatively large discrepancy between plant spacing in the row and spacing between the plant rows that is commonly observed in commercial tomato-production fields.

The leaf-N concentration below which a reduction in Pg occurs (FNPGN) was reduced from 4.5% to 4.0% N. As a result, the rate of photosynthesis became less readily reduced by low concentrations of N in the leaf tissue for tomato than for the leguminous peanut plant. A value of 1.36 mg CO_2 m^{-2} s^{-1} for the light-saturated leaf photosynthesis rate (LFMAX) for tomato was obtained from field measurements. This value is used for the leaf-level canopy photosynthesis option available in the CROPGRO model. The values reported here for PHT_{max}, K_p, and K_{can} are being used in the current version of the growth model in theTMGRO940.SPE file of CROPGRO.

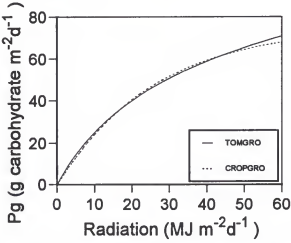


Fig 9-1. Simulated daily Pg values (g carbohydrate $m^{-2}d^{-1}$) as a function of radiation for a tomato crop (LAI=5) using TOMGRO (Jones et al., 1989b) and the matching prediction of Pg values by CROPGRO assuming values for the fitted photosynthetic parameters PHTmax and Kp of 75.54 and 0.0386, respectively.

Phenology

During initial parameter modification an existing peanut ecotype file (PNGRO940.ECO) and cultivar file (PNGRO940.CUL) were adapted for tomato. However, the basic concepts of vegetative and reproductive development stages as defined for peanut by Boote (Boote et al., 1986) were maintained. Since fresh-market tomato is commonly transplanted, modification was required in parameterization of the initial crop development stages. The dry weight of the plant at transplanting was added as an input parameter in the TMX file, and is used by the model to initialize leaf area and plant weight at the time of planting. The time required from seeding until the first true leaf stage was subsequently set to zero. The rate of node appearance (TRIFL) for tomato is also faster than that of peanut, with respective TRIFL values of 0.52 and 0.39 nodes d^{-1}. Rate of early leaf-area development for tomato was assumed to be sink-limited, though the node number to which plants remain sink-limited (VSSINK) was reduced from 7.5 to 4.0. The XVGROW look-up function, which relates node number to maximum possible leaf area during the sink-limited phase, was recalibrated for tomato.

Vegetative growth and partitioning

Leaf characteristics of tomato also differ appreciably from those of peanut. To accommodate these differences, a number of modifications were made in the crop- and cultivar-specific parameters. The value of the leaf size parameter (SIZLF) was increased from 20 to 300 cm^2, to account for the much larger relative leaf size of tomato. The value

of the specific leaf area (SLAVAR) was also increased from 280 to 340 $cm^2\ g^{-1}$, to accommodate the relatively higher area/weight ratio of tomato leaves.

Partitioning of assimilates among vegetative plant parts differs between crops and also depends on the growth stage of the crop itself (Boote et al., 1986). The CROPGRO model uses partitioning coefficients to calculate the allocation of photosynthates to the new growth of leaves, stems (including leaf petioles), and roots. Since these values change over time, the partitioning to leaves (FRLF) and stems (FRSTM) is calculated for a number of successive growth intervals and these values are then linked to "mid-point" node numbers and listed via a look-up table in the species (SPE) file.

Measured dry weights of leaves and stems for the growth studies were used to calculate the values of FRLF and FRSTM and to estimate root weights. Estimated root weights were refined by adding estimated carbon losses due to root sloughing and root senescence. Estimated carbon losses were based on values reported in the literature (Smuckers, 1984) along with observations made in the field. The rationale for introducing this correction factor was the relatively large discrepancy between the fraction of photosynthates that were calculated as partitioned to the roots and the actual root biomass that was recovered by excavation of root systems formed under production systems with shallow water tables (McNeal et al., 1995). The measured accumulation of dry matter in the roots by season's end was on the order of 3-5% of the total biomass, which appears to be low compared to values reported (e.g., Jackson and Bloom, 1990) for production systems with a deep water table. Low values may be related to the shallow and fluctuating water table, which may enhance root respiration, root sloughing, and root die-back

(Smuckers, 1984). Using actual root biomass data for calibration would therefore result in an under-prediction of dry matter partitioning to the roots and an over-prediction of dry matter partitioning to stems and leaves. In a previous approach (Scholberg, 1994), the root partitioning coefficients were based on values reported in the TOMGRO documentation (Jones et al., 1989b). With this approach, predicted root weights were 5- to 10-fold greater than actual values (Scholberg, 1994). As a result, root density would also be over-predicted, which could cause future problems during calibration of the water- and nutrient-balance portions of the model. It was therefore decided to recalibrate the vegetative partitioning coefficients based on revised estimated root weights (i.e., based on revised TRIFL values) and to increase the value of the root senescence factor (RTSEN) from 0.01 to 0.03. The increase in assumed senescence was in part based on the difference in morphology between peanut and tomato roots, and in part on the perceived need to account for increased root senescence in the presence of shallow water tables. To calculate FRLF for a specific node number, the increment in leaf weight (dBL) between two sampling dates was divided by the increment in total vegetative biomass (dVB). Similarly, FRSTM was calculated by dividing dSTM by dVB. Using linear regression, a functional relation was established between "mid-point" node number and partitioning coefficients. Resultant values for assimilate partitioning to roots, leaves, and stems are shown in Figs. 9-2a to 9-2c. An outline of the partitioning coefficients for photosynthates to roots, stems, and leaf blades, along with parameterization of the XVGROW look-up function (discussed previously in the phenology section), is presented in Table 9-3. Towards the end of the growing season, weight increments between sampling dates

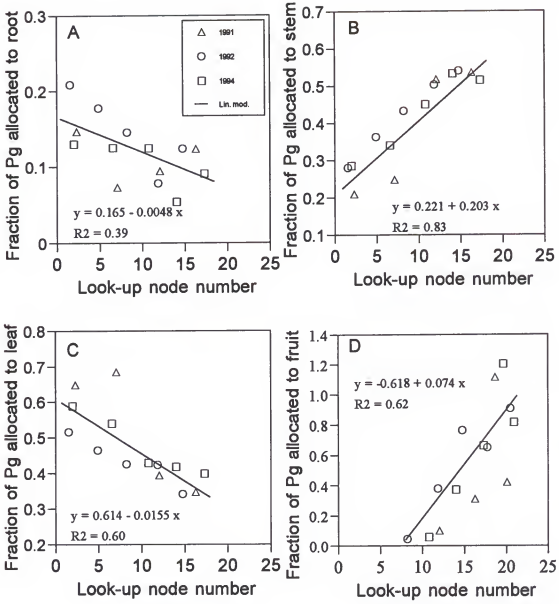


Fig. 9-2. Partitioning of photosynthates within the vegetative assimilate fraction to roots (a), stems (b), leaves (c); and partitioning of total photosynthates to fruits (d). The calculated data points for the 1991, 1992, and 1994 growing season were fitted using linear regression (Lin. mod.), expressing dry weight partitioning to roots (y), stems (y), leaves (y), or fruit (y) as a function of node number (x).

became relatively small compared to overall variation between individual plants. Apparent differences between subsequent sampling dates may thus be largely due to inherent variation within the plant population, combined with senescence and retranslocation of assimilates to the fruits. As a result, partition coefficients cannot simply be deduced from observed biomass values of different organs, since other processes including senescence and reallocation of photosynthates affect overall dry matter accumulation. Increases in vegetative biomass over time eventually approach zero and may even become negative in some circumstances. From Table 9-3 it may be concluded that tomato plants initially invest most of their assimilate into a rapid build up of photosynthetic production capacity (leaves). Over time, however, plants increase the partitioning of photosynthates into structural stability (stems) required to support the subsequent fruit load.

Table 9-3. Maximum potential leaf area and partitioning of photosynthates to roots, stems, and leaves of tomato as a function of vegetative stage (node number).

Look-up Node No.	Maximum Potential Leaf Area	Partitioning of Pg		
		Roots	Stems	Leaves
	(cm^2)	--------fraction----------		
0.0	15.4	0.17	0.22	0.61
1.7	28.1	0.16	0.25	0.59
4.3	83.4	0.14	0.31	0.55
5.9	210.0	0.14	0.34	0.52
6.9	340.0	0.13	0.36	0.51
8.5	--	0.12	0.40	0.48
12.3	--	0.11	0.47	0.42
13.4	--	0.10	0.49	0.41
14.0	--	0.10	0.51	0.40

Reproductive growth

It was conceptualized that a tomato fruit could be perceived as a seeded pod with a very low seed to total fruit dry weight ratio. Based on experimental data, the value of THRSH (which expresses this ratio as a percentage) was reduced from 80% (for peanut) to 5.2%. The weight per seed (WTPSD) value used for tomato was also reduced to 0.0035 g (compared to 0.57 for peanut), while the potential seed number per fruit (SDPDV) was increased from 1.7 to 250.

Based on values reported in the literature, the time required for tomato fruit growth to be completed (LNHSH) was initially estimated as 30 days (Wolf et al. 1986). However, based on the results presented in Chapter 7, a value of 38 days appears to be more appropriate, which is appreciably longer than the 20 days used for peanut shells. Based on experimental observations, the time between first seed formation and physiological maturity (SD-PM) was also reduced from 83.7 to 50.0 thermal days to shorten the life cycle. After fruit initiation, fruits increasingly compete with vegetative parts for assimilates. Unlike more determinant processing-tomato cultivars or crops such as soybean, fresh-market tomato shows a more gradual shift towards reproductive growth over time.

The average value of the partitioning coefficient to the fruits during the time of maximum total sink strength for the fruits (node number >16) was on the order of 0.77 (Fig 9-2d). This value subsequently was used as an estimate for the XFRT parameter, which is the maximum limit for partitioning of assimilates to the fruit. Later in the growing season, values close to or even in excess of 1.0 may occur. This is related to the "shut

down" of both leaf and stem growth, and the retranslocation of photosynthates from these organs to the fruits (Scholberg 1994).

Model Comparison with 1994 Field Data

Calibration was continued until the predicted time-series values of nodes, LAI, and SLA; and the dry weights of stems, leaves, fruits, and above-ground biomass, fitted actual field data for the 1994 growing season at Bradenton. After this calibration of the model, predicted values for node number, plant height, LAI, and SLA; and dry weights of fitted observed values for stems, leaves, fruits, and above-ground biomass; closely matched actual field measurements (Figs. 9-3a to 9-3f). A further increase in the rate of node appearance from 0.45 (October 1994 version) to 0.52 nodes d^{-1} resulted in an even better fit of the experimental data (Fig. 9-3a). Changes in the partitioning coefficients to this point in time have not affected canopy development or leaf and stem weight appreciably. However, the reduced partitioning of assimilates to the roots along with increased root senescensce rates in the modified 940 model version resulted in a reduction of predicted root weights by fifty percent compared to the 1994 simulation results (Scholberg, 1994).

Sensitivity Analysis

Increasing PHT_{max} from 61 to 75 (estimated value for tomato) resulted in a sharp increase in leaf area index and fruit dry weight (Figs. 9-4a and 9-4b, open triangles and open circles, respectively). Increasing K_p from 0.025 (the value used for peanut) to 0.0386 (the estimated value for tomato) resulted in even further increases in simulated values

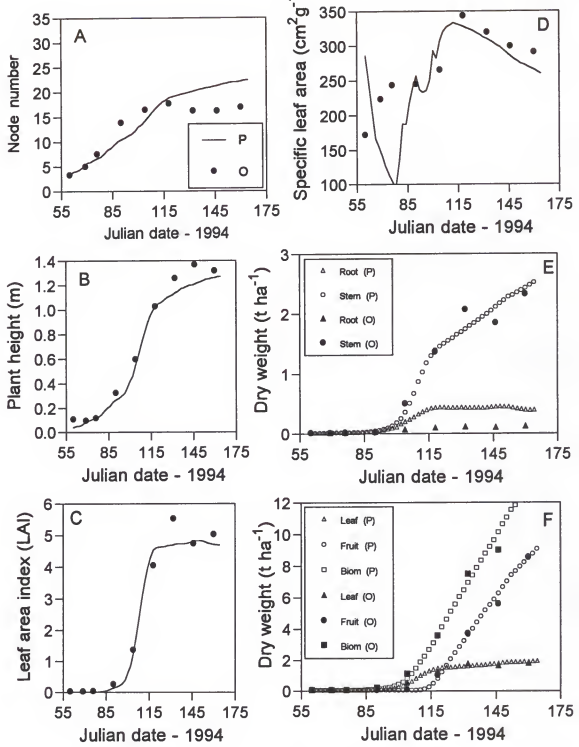


Fig. 9-3. Predicted (P) and observed (O) node number (a), plant height (b), leaf area index (c), specific leaf area (d), root and stem weight (e), and leaf, fruit, and total biomass weight (f) for tomato at Bradenton during the spring 1994 growing season.

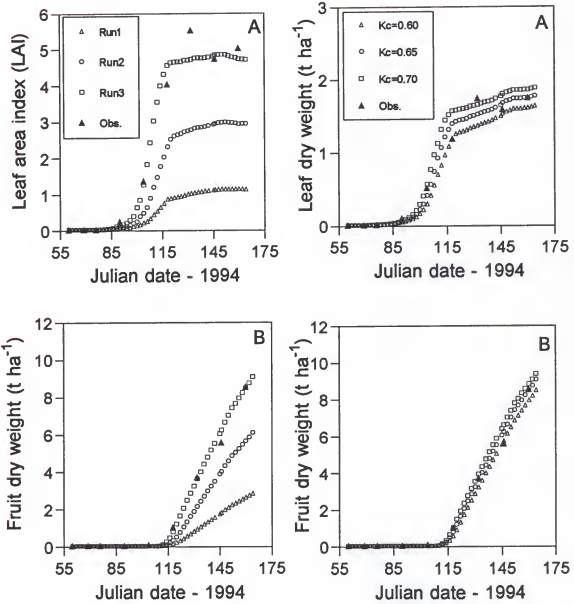


Fig. 9-4. Simulated effects of changes in Kp (curvature coefficient; values were 0.025, 0.025, and 0.040 for run #1, run # 2, and run # 3, respectively) and PHTmax (maximum daily photosynthetic production capacity under optimal conditions; values were 61, 75, and 75 for run#1, run #2, and run #3, respectively) on predicted LAI values (a) and fruit dry weight (b) in comparison to the 1994 field data for Bradenton.

Fig. 9-5. Simulated effects of changes in Kc (light-extinction coefficient) on predicted leaf dry weight and fruit dry weight in comparison to the 1994 field data for Bradenton.

(Figs 9-4a and 9-4b, open circles and open squares, respectively). The value of PHT_{max} is indicative of the capacity of the photosynthetic apparatus at infinitely high radiation levels, whereas K_p reflects the efficiency of the system at lower radiation levels.

The value of the canopy light extinction coefficient (K_{can}) is typically 0.75 for equidistant plant spacings but, for crops with greater row spacings, the value may be more realistically reduced to 0.60. Decreasing values of K_{can} resulted in reduced values of LAI (Fig. 9-5a), and also in reduced fruit dry weight (Fig 9-5b). The CROPGRO model appears to be very responsive to changes in K_p, PHT_{max}, and K_{can}. This is probably related to the impact of these parameters on the total available assimilate pool, which appears to be one of the main driving forces for the model.

Changes in partitioning coefficients appeared to have little effect on predicted stem weights (Fig. 9-6a). However, conversion from peanut to tomato coefficients resulted in an increase in dry matter partitioning to the leaves during initial growth (Fig. 9-5b) and to roots during the latter part of the growing season (Fig. 9-5c). With the use of the 1996 partitioning coefficients, predicted values of both leaf and stem weight were slightly reduced during initial growth whereas, for the latter part of the growing season, the reverse was true (Figs. 9-5b and 9-5c). However, changes in partitioning coefficients had a more pronounced effect on predicted root weights (Fig. 9-5c) and, along with an increase in root senescence (Fig. 9-5d), this resulted in a reduction of predicted root weight by roughly fifty percent. It should be noted that observed root weights for the 1994 growing season were about half of those for previous seasons, due in part to a less-complete recovery of the root system because of the sampling procedure used. Reported

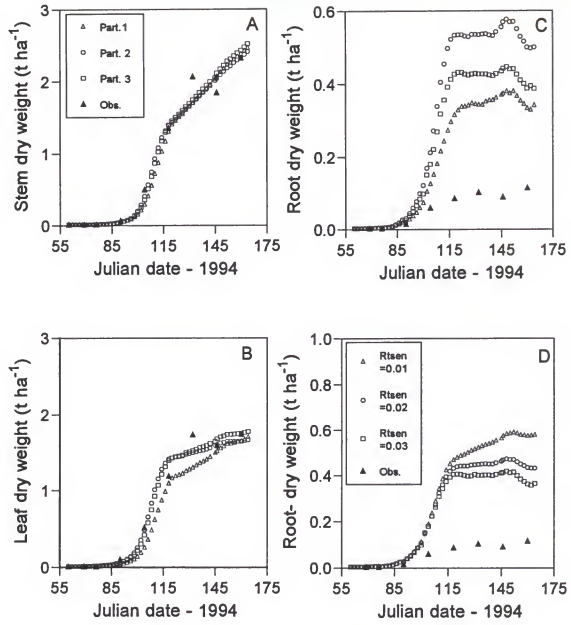


Fig. 9-6. Simulated effects of changes in vegetative partitioning coefficients (part 1: original peanut values; part 2: 1994 tomato coefficients; and part 3: revised tomato coefficients) on predicted stem dry weight (a), leaf dry weight (b),and root dry weight (c); and simulated effects of changes in root senescence (Rtsen) on root weight (d) in comparison to 1994 field data for Bradenton.

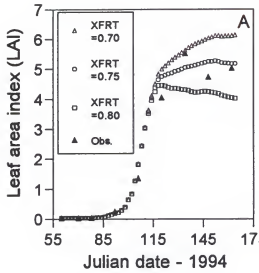
weights for more complete root recovery are on the order of 0.25 t dw ha^{-1} for shallow watertable systems (McNeal et al., 1995). Predicted root dry weights on the order of 0.4 t dw ha^{-1} appear, therefore, to be more realistic than previously predicted values of 0.85-1.1 t dw ha^{-1} (Scholberg, 1994).

The effects of changing the fraction of photosynthates partitioned to the fruit (XFRT) on LAI values and fruit dry weights are shown in Figs. 9-7a and 9-7b. With increased values of XFRT, canopy expansion during the onset of fruit development was shut down completely (Fig. 9-7a), whereas only a reduction in stem growth occurred (data not shown). Fruit dry weight increased as XFRT increased, with a value of between 0.75 and 0.80 giving the best fit to the data (Fig. 9-7b). It can be concluded that the predicted accumulation of dry matter in stems and leaves after initial fruit set is greatly affected by the value of XFRT. Low values resulted in prolonging the vegetative growth phase, whereas high values resulted in over-prediction of fruit yields (Fig. 9-7b).

Increasing the value of SLAVR (model input value for SLA under standard conditions) resulted in increased simulated values for LAI (Fig. 9-8a) and SLA (Fig. 9-8b). For the 1994 data set, a value of 350 seemed to give the best results, with the model appearing to be moderately sensitive to changes in this parameter.

Model Simulation Versus Other Data Sets

Increasing the value of TRIFL from 0.45 to 0.52 nodes d^{-1} resulted in a better fit of plant node numbers (Figs. 9-9a and 9-10a). Reported node numbers for the latter part of the 1992 growing season appeared to be too high (it is possible that some first-order



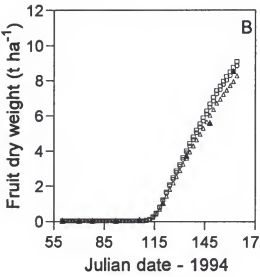
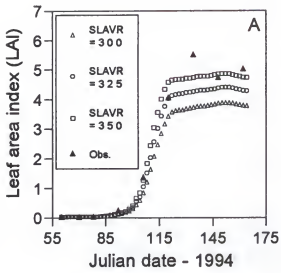


Fig 9-7. Simulated effects of changes in XFRT (the fruit partitioning coefficient) on predicted LAI values (a) and predicted fruit dry weight (b) in comparison to 1994 field data for Bradenton.



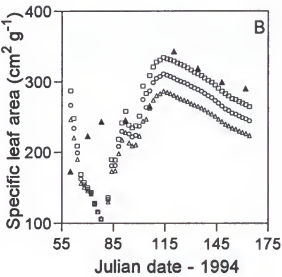


Fig. 9-8. Simulated effects of changes in SLAVR (the SLA under standard conditions) on predicted leaf a rea values (a) and predicted specific leaf area (b) in comparison to 1994 field data for Bradenton.

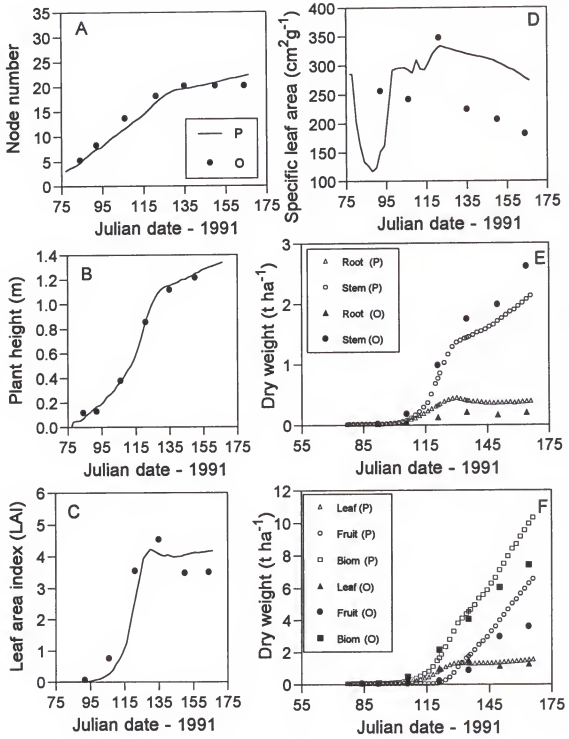


Fig 9-9. Predicted (P) and observed (O) node number (a), plant height (b), leaf area index (c), specific leaf area (d), root and stem weight (e); and leaf, fruit, and total biomass weight (f) for tomato at Bradenton during the spring 1991 growing season.

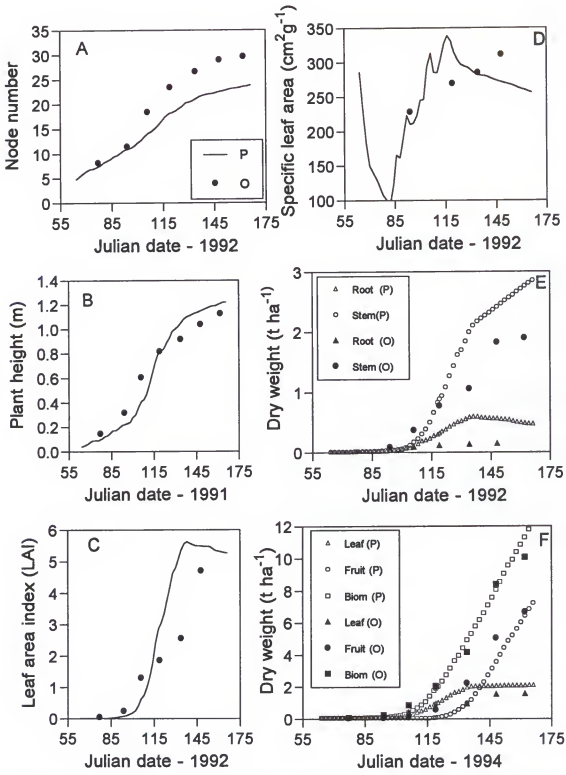


Fig 9-10. Predicted (P) and observed (O) node number (a), plant height (b), leaf area index (c), specific leaf area (d), root and stem weight (e); and leaf, fruit, and total biomass weight (f) for tomato at Bradenton during the spring 1992 growing season.

nodes were included during counting). Predicted canopy height matched observed values closely (Figs. 9-9b and 9-10b), with similar results being obtained for canopy width (data not shown). Early-season LAI values were slightly under-predicted whereas, for the latter part of the growing season, the reverse was true (Figs. 9-9c and 9-10c). The relatively slow rate of mid-season canopy development for the 1992 growing season appeared to be unusual and may have been indicative of moderate water stress. During the 1991 growing season, late-season SLA was over-predicted (Figs. 9-9d and 9-10d). However, observed SLA values (Fig. 9-9d) appeared to be relatively low compared to those reported for the 1992 (Fig. 9-10d) and 1994 (Fig. 9-3d) seasons.

Stem weights were slightly under-predicted during the entire 1991 growing season (Fig. 9-9e). For the 1992 growing season, on the other hand, stem weights were under-predicted during initial growth and over-predicted during the latter part of the growing season. More vigorous stem growth may have been related to the likely N-stress observed during the latter part of the season. Root weights were still over-predicted, with reported root weights being roughly only 30-50% of predicted root weights (Figs. 9-9e and 9-10e). Reported root weights for production systems with a deep watertable, on the other hand, can be as high as 1.0 t dw ha^{-1} (Jackson and Bloom, 1990). According to model predictions, a rooting depth of 2.0 m should have been reached within three months after transplanting. However, the presence of a spodic horizon at a soil depth of 0.4-0.5 m in Bradenton, and the shallow watertable typically associated with it, appeared to eliminate or inhibit root growth below a soil depth of 30-50 cm. Increasing the bulk density of

lower soil layers appeared to have little effect on predicted root growth, which appears to be unrealistic.

Fruit weights were over-predicted for 1991 and under-predicted for the 1992 growing season (Figs. 9-9f and 9-10f). The predicted onset of fruit production was about five days too early and seven days too late for the 1991and 1992 growing seasons, respectively. This "timing" effect may be related to N-fertilization rates. Relatively high fertilization rates (1991) may delay fruit growth, whereas reduced N-rates may promote earliness. Simulated total above-ground biomass fitted observed data fairly well during both seasons, except that observed biomass started to "trail off" near the end of the season in both experiments (Figs. 9-9f and 9-10f). This phenomenon may be related to nutrient stress (Bradenton 1992), and to uncertainties in phenology characterization and lack of simulated N-deficiency in the crop model during the simulations presented here. Effects of including both water- and N-stress on predicted values for a number of independent data sets for a number of locations at Florida and in Puerto Rico will be discussed in a separate research report.

Comparison of Leaf-Level vs Canopy Photosynthesis

Comparison between leaf-level and canopy-level photosynthesis shows that the use of both methods gave similar results. However, the former resulted in more accurate early-season predictions for the 1991 and 1992 data sets (Figs. 9-11). Later in the growing season, predicted values of both leaf area index and biomass were lower when using the leaf-level photosynthesis model. Predicted values for midday canopy photosynthetic rates

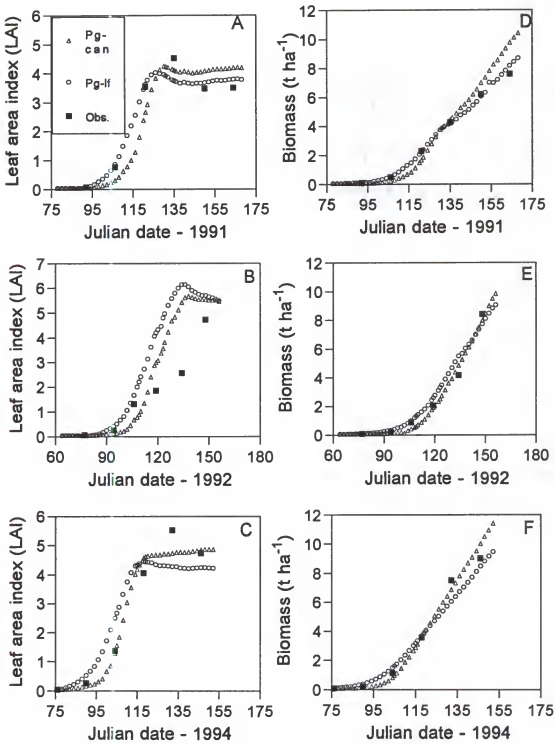


Fig 9-11. Simulated effects of using canopy (Pg-can) vs leaf (Pg-lf) photosynthetic routines on leaf area index (a, b, and c); and total biomass (d, e, and f); in comparison to 1991 (a and d), 1992 (b and e), and 1994 (c and f) field data for Bradenton.

were on the order of 1.98 mg CO_2 m^{-2} s^{-1}, and compared favorably with values reported for greenhouse tomato (Jones et al., 1989b).

Conclusions

Results from initial modifications of the generic CROPGRO model to describe field-tomato growth show both the adaptability and robustness of the model. The procedure presented here may also be employed as a "blueprint" for future CROPGRO adaptations to other tomato varieties or other vegetable crops. From the results presented above, it may be concluded that the model adequately describes plant growth of field-grown tomato for conditions where growth is not limited by nutrient- or water-stress. In its current form the model should provide potential users in the agricultural research community with reasonably accurate yield predictions for field-grown tomato under near-optimal conditions. However, during initial adaptation and calibration of the model, effects of water- and N-limitations were not included. Based on the water and nutrient distribution patterns presented in Chapter 6, it may be concluded that the use of a one-dimensional solute transfer cannot describe actual distribution patterns vegetable-production beds. A one-dimensional approach may not be sufficient to describe solute transfer for specific irrigation systems (such as drip irrigation) nor can it account for the effects of plastic mulch on rainfall infiltration. Further limitations to the currently adapted version of the CROPGRO model for tomato include its inability to predict marketable fruit yields. Further development of a user-friendly interface also appears desirable to make the model more accessible to potential users in the agricultural community.

CHAPTER 10
SUMMARY AND CONCLUSIONS

This study was designed to support the adaptation of the TOMGRO and CROPGRO models to describe the growth of field-grown tomato. This chapter summarizes the main conclusions reached in each phase of this study as related to the objectives outlined in Chapter 1.

Tomato is of one of the most important vegetable crops in the world, with a world-wide production of 40 million tons and a total acreage of approximately 2 million ha. Yield levels may range from 1 to 300 t ha^{-1}, depending on the production system. There is a large existing body of knowledge on the effects of growth factors on tomato growth and fruit yield under specific conditions. However, little effort has been made to synthesize this information into a general knowledge base that could be used to predict crop performance for a range of production environments. Considering the challenges agriculturists face during the next century, the reductionist approach that has prevailed in agricultural research during most of this century may no longer suffice. Some of the problems the human race is facing may require a more "holistic" and "global" research approach instead. The use of innovative technology including state-of-the-art computer technology should allow us to increase resource-use efficiency and total food production with minimal environmental impacts. Computer technology should also facilitate a more

ready distribution and sharing of information between different regions, and may prove indispensable when identifying and evaluating innovative technology. Although the future will always be "uncertain", the use of computer models should allow us to evaluate future "what if" scenarios on a global scale and may assist in defining future production policies.

Potential yield for field-grown tomato depends on cultivar, radiation and the duration of the production season. Under Florida conditions, potential fresh-weight yields on the order of 80-150 t ha^{-1} are possible for a production season of 90 to 110 days in length. Overall biomass (dry weight) accumulation is on the order of 6 to 12 t ha^{-1}, and fruit dry weight harvest indices range from 0.53 to 0.71. Dry matter accumulation by roots, stems and leaves accounts for roughly 3%, 23% and 17% of the total biomass, respectively. Radiation use efficiency (RUE) for tomato was found to be 0.87 g dry weight MJ^{-1} m^{-2}, with near-complete light interception being attained at LAI values around 4 to 5. Maximum rates of dry matter accumulation were on the order of 20 to 25 g $plant^{-1}$ d^{-1} when spaced at 11,000 plants per ha. Observed differences in fruit yields between subirrigated and drip-irrigated crops were commonly related to relatively lower LAI values for the latter, due to inadequate water- and N-management. Although vegetative growth for drip- irrigated crops was commonly less vigorous compared to well-watered and well-fertilized subirrigated crops, potential fruit yields under optimal management conditions appeared to be similar for both irrigation management systems.

Based on a detailed analysis of the literature, crop water requirements of tomato were on the order of 450 to 550 mm, depending on environmental conditions and the length of the production season. In locations with rainfall above 100 mm, contributions of

rainfall to crop water requirements may be substantial, and rainfall must therefore be included when evaluating the yield response to irrigation water. Water use efficiencies for drip-irrigated tomato were on the order of 0.19 and 0.39 t fruit mm^{-1} when irrigation scheduling was based on pan evaporation and tensiometer readings, respectively. Water stress typically resulted in a more pronounced reduction in fruit number than in fruit size. Overall reduction in fresh fruit weight was also more pronounced then reduction in fruit dry weight. Based on the results of a field experiment, water stress during initial growth can reduce canopy development appreciably. However, it may also result in better adaptation of the crop to water stress, and subsequently in relatively high fresh fruit yields. Water stress during fruit development, on the other hand, only reduced fruit yield.

Severe N stress resulted in the formation of fewer and smaller, but thicker, leaves. Fruit size was not greatly affected by N rate, whereas severe N-stress resulted in a reduction of fruit number by 60-70%. With increasing N-rates, LAI increased from 0.6-0.8 to 2.7-3.5 on coarse-textured soils and from 0.9-1.9 to 2.5-3.5 on fine-textured soils. Concurrent increases in RUE values were typically less then 30%. Lower RUE under N-limited conditions could be related to a decrease in N content of the most recently matured leaves from 4 to 1.5%, and a concurrent reduction in leaf photosynthesis by 25-35%. Overall leaf N concentrations dropped from 5.5-6.5% during initial growth to 2.0-3.5% at final harvest even for well fertilized crops. N concentrations for fruits and stems were on the order of 3.0-3.5% N and 1.5-2.5% N, respectively. Severe N stress affected leaf and stem N concentration most drastically, whereas N concentrations in fruits were affected to a considerably lesser extent. N-accumulation by the tomato crop increased

from 23-50 to 96-336 kg N ha^{-1} as N-rates increased from 0 to 333 kg N ha^{-1}. Apparent N-fertilizer recovery decreased as N-rates increased, with values ranging from 0.36-0.74 and 0.61-0.96 for drip-irrigated and subirrigated crops, respectively.

Total root length increased from 3 m at transplanting to 1500-3000 m per plant at harvest. Maximum root length densities in commercial production beds ranged from 2.6-5.0 cm cm^{-3} near the bed center to 0.7-1.2 cm cm^{-3} near the edge of the bed. For subirrigated crops, root growth was often confined to the upper 30 cm of the soil profile, due either to the presence of a compacted and often highly acidic subsurface layer or to the anaerobic conditions associated with this hard pan. Residual soil N concentrations in mulched beds typically were well below 5 ppm N. With drip irrigation, solute accumulation occurred at the edge of the wetting front near the upper edges of the production beds. With the use of subirrigation, solutes typically remained concentrated in the vicinity of the fertilizer band as long as a minimum depth to the water table of 20-30 cm was maintained.

After an initial lag phase, fruit dry weight and fresh weight increased linearly with time. Maximum growth rates were on the order of 5 and 0.3 g d^{-1} for fresh and dry fruit weights, respectively. Fruits attained maximum size within 38-45 physiological days after anthesis, and total fruit yield was closely related to the amount of radiation intercepted during the period 6 weeks prior to harvest. Fruit dry matter percentage followed an exponential decay function, decreasing from approximately 12% at anthesis to 5% at fruit maturation. Fruit weight could be predicted using a cubic relationship after introducing a fruiting coefficient to account for deviations from a perfectly spherical fruit shape.

By including a branching routine in an existing crop model (TOMGRO) developed for greenhouse tomato, it was possible to describe the vegetative growth of field-grown tomato. However, this model did not adequately describe actual fruiting characteristics and neither did it account for the effects of water and nutrient stresses on plant growth and fruit yield. Based on these results it was concluded that the TOMGRO model in its current form was not very useful for yield predictions of field-grown tomato.

By modifying crop- and cultivar-specific parameters of a generic crop model (CROPGRO), it was possible to describe growth and fruiting characteristics of field-grown tomato for a number of locations and cropping seasons throughout Florida. In its current form, the CROPGRO model is well-calibrated for field-grown tomato, and the model should provide potential users with reasonably accurate yield predictions under near-optimal growth conditions. However, during initial adaptation and calibration of the model, effects of water and N limitations were not included. Including these effects sometimes resulted in unrealistic predictions of crop growth and solute transfer in production beds. Dissimilarities between observed and predicted plant growth and N accumulation by the crop could, in many cases, be attributed to the use of only a one-dimensional solute-transfer model. A one-dimensional approach may not be sufficient to describe actual solute transfer of drip-irrigated crops nor can it account for the effects of plastic mulch on rainfall infiltration. Further limitations to the currently adapted version of the CROPGRO model for tomato include its inability to predict fresh or marketable fruit weight. Development of a user-friendly interface also appears desirable in order to make the model more accessible to potential users in the agricultural community.

Further adaptation of the CROPGRO, including the development of a marketable fresh-fruit routine and a more detailed water balance, are needed for broader use of the model to alternative production systems. Finally, data obtained from the literature and historical records can then be used for validations and testing of the model under different production conditions.

APPENDIX A
PRODUCTION COSTS, PRODUCTION SYSTEMS, AND GRADING STANDARDS FOR TOMATO

Table A-1 Estimated production costs of commercial tomato crops for the Manatee/ Ruskin area, North Florida, and Southwest Florida[1]

	Production cost ($ acre^{-1})		
	Manatee Area	North Florida	Southwest Florida
Operating costs			
Transplants	224 (2.2)[3]	315 (2.7)	385 (3.4)
Fertilizer and lime	350 (3.4)	311 (2.7)	259 (2.3)
Pesticides	1063 (10.4)	1097 (9.6)	860 (7.7)
Labor	364 (3.6)	345 (3.0)	244 (2.2)
Machinery	267 (2.6)	210 (1.8)	336 (3.0)
Interest	121 (1.2)	169 (1.5)	161 (1.4)
Miscellaneous	705 (6.9)	1684 (14.7)	1434 (12.8)
Total operating costs	3093 (30.3)	4133 (36.1)	3678 (32.9)
Fixed costs			
Land rent	400 (3.9)	350 (3.1)	450 (4.0)
Machinery	214 (2.1)	131 (1.1)	174 (1.6)
Management	717 (7.0)	444 (3.9)	828 (7.4)
Overhead	897 (8.8)	667 (5.8)	1035 (9.3)
Total fixed costs	2228 (21.8)	1592 (13.9)	2488 (22.3)
Total preharvest costs	5322 (52.1)	5725 (50.0)	6166 (55.2)
Harvesting and marketing costs	4900 (47.9)	5712 (50.0)	4998 (44.8)
Total costs	10222 (100)	11437 (100)	11164 (100)

[1] Source: Smith and Taylor (1994)

2 Reported values for a spring crop assuming 7,260 linear bed feet and a yield of 1400 cartons per acre

[3] Values in parentheses express specific costs as a percentage of total production costs

Table A-2. Tomato maturity classes and criteria for fruit maturity stages

Maturity stage	Days to full color [1]	Criteria
Immature green	19-23	Fruits are dull green, seeds are white and are not fully developed, and fruit gel has not yet been formed. The fruit skin rubs off but fruit will not ripen properly when harvested at this stage.
Mature green	9-13	Fruits are glossy and are bright or whitish green, seeds are light-brown, and both seeds and fruit gel are fully developed.
Breaker	8	The blossom end of the fruit shows yellow to pink blush.
Turning	7	10-30 % of the fruit surface shows pink color.
Pink	6	30-60 % of the fruit surface shows pink or red color.
Light red	3	60-90 % of the fruit surface shows pinkish-red color
Firm ripe	1	More than 90 % of the fruit surface shows red color, but fruit is still firm.
Table ripe	0	Full color development and fruit starts to soften.

[1] Measured at 20 °C, adapted from Peirce, 1987.

Table A-3. Overview standards for grades of fresh market tomato

Size classification	Minimum size (mm)	Maximum size (mm)
Florida size classification [1]		
7 x 7	55	59
6 x 7	57	65
6 x 6	63	71
5 x 6 and larger	70	--
USDA grades [2]		
Extra small	48	54
Small	54	58
Medium	58	64
Large	64	73
Extra large	73	88
Maximum large	88	--

[1] Hochmuth, 1984; [2] United States Department for Agriculture, 1984

Table A-4 Overview of some commonly denoted production systems for tomato

Production system	Production features											
	Oveall use of		Control level								Production	
	external inputs	manual labor	Water	Nutr.	Pests	Light	Temp.	CO_2	Seas.	Price	Yield ($t\ ha^{-1}$)	Quality
A: Small-scale production												
- Collection of wild fruits	0	1	0	0	0	0	0	0	0	0	< 0.01	1
- Small-scale extensive prod.	1	1-2	0-1	0-1	0-1	0	0	0	1	0	1-10	1
- Small-scale intensive prod.	2-3	3	2	2-3	2-3	0	1	0	1-2	0-1	15-45	2-3
B: Commercial production												
I Fresh-market production												
1 Field production												
- Non-irrigated	2-3	2	1	2	2-3	0	1	0	1	1	10-45	2-3
- Furrow irrigated	2-3	2-3	2	2-3	2-3	0	1	0	1-2	1-2	30-75	2-3
- Overhead irrigated	3	2-3	2-3	2-3	2	0	1-2	0	1-2	1-2	30-75	2-3
- Subsurface irrigated	2-3	2-3	2	2-3	2-3	0	1	0	1-2	1-2	30-90	2-3
- Micro irrigated	3-4	3	3-4	2-4	2-3	0	1	0	1-2	1-2	30-120	2-4
2 Greenhouse production												
- Non-heated	3-4	3-4	4	3-4	3-4	1-3	2	1-2	2-3	2	100-200	2-4
- Heated	4	4	4	3-4	4	2-4	3-4	3-4	4	2-3	200-350	3-4
II Processing tomato prod.												
- Paste production	2-3	2	2-3	2-3	2-3	0	1	0	1-2	2-3	60-150	2
- Canned tomato prod.	2-3	2	2-3	2-3	2-3	0	1	0	1-2	2-3	40-120	2-3

Source: Adapted from Scholberg, 1987
Keys: 0=None,1=Little, 2=Intermediate, 3=High, 4=Very high

APPENDIX B
WEATHER AND SOIL CHARACTERIZATION DATA

Table B-1. Overview of weather data (spring), for Bradenton 1991, 1992, 1994, and 1995.

	Tmax (°C)				Tmin (°C)				Total Radiation (MJ m^{-2} d^{-1})			
Period (Julian dates)	1991	1992	1994	1995	1991	1992	1994	1995	1991	1992	1994	1995
51-60				26.7				17.9				12.0
61-70		28.6	28.4	25.2	15.0	16.7	17.3	14.2	16.4	21.0	16.9	17.9
71-80	23.3	22.4	24.4	25.1	12.9	11.0	12.4	14.6	15.0	18.1	22.9	17.6
81-90	28.1	24.2	28.5	27.3	18.4	13.1	18.9	16.6	18.3	19.9	19.6	21.1
91-100	27.2	24.0	27.1	25.5	17.5	14.2	14.6	15.9	19.1	19.3	23.1	16.5
101-110	29.3	28.3	30.8	29.1	19.2	17.5	19.7	17.6	21.4	22.0	22.6	23.3
111-120	29.7	26.6	30.0	28.6	20.2	18.0	19.6	19.1	20.8	20.3	20.9	18.4
121-130	32.0	25.7	30.7	32.1	21.8	14.1	20.2	20.7	23.3	24.5	24.4	24.2
131-140	31.6	29.2	31.4	33.4	21.1	17.1	21.3	22.7	11.8	25.1	22.8	25.4
141-150	30.3	30.1	29.5	32.1	23.4	19.2	16.9	21.0	15.9	26.2	25.3	23.0
151-160	30.4	32.4	30.6	30.2	21.6	22.1	21.6	22.8	19.8	22.2	17.7	17.9
161-170	30.1	32.6	32.7		21.3	23.0	23.5		20.4	23.8	25.5	
Seasonal Average	28.7	27.6	29.5	28.7	19.3	16.9	18.7	18.5	18.4	22.0	22.0	19.8

Table B-2. Overview of weather data (spring) for Gainesville 1995 (G-95), Gainesvile 1996 (G-96), Immokalee 1995 (I-95), Puerto Rico 1995 (P-95), and Quincy 1995 (Q-95).

Period	Tmax (°C)					Tmin (°C)					Total Radiation (MJ $m^{-2} d^{-1}$)				
(Julian d.)	G-95	G-96	I-95	P-95	Q-95	G-95	G-96	I-95	P-95	Q-95	G-95	G-96	I-95	P-95	Q-95
1-10				28.9					17.7						16.5
11-20				28.9					18.3						16.1
21-30			21.3	29.0				8.1	18.0					14.9	15.0
31-40			19.6	30.9				7.4	16.8					16.5	17.3
41-50			25.0					13.2						14.9	
51-60			24.7					12.6						16.5	
61-70			25.6					14.3						17.9	
71-80		22.3	25.8				5.2	10.9					17.7	18.0	
81-90	27.7	24.3	28.5		25.8	14.4	10.5	16.5		14.1	16.6	16.3	22.6		14.9
91-100	25.6	24.4	27.0		22.6	11.4	9.6	16.0		8.8	17.0	17.7	18.5		18.8
101-110	3.07	26.9	30.0		28.1	13.4	7.8	16.8		13.2	21.3	21.7	24.3		21.9
111-120	29.7	31.1	29.3		26.0	14.5	15.4	19.0		12.9	19.3	23.3	19.8		20.2
121-130	33.5	31.8			29.7	17.4	16.3			14.9	19.6	24.1			18.6
131-140	33.2	32.4			30.2	20.6	16.6			19.1	17.7	23.5			17.0
141-150	33.4	33.4			31.4	18.6	20.6			17.9	20.5	18.3			22.6
151-160	32.9	32.4			30.8	22.2	18.0			20.2	16.4	22.2			15.8
161-170	32.4	32.7			30.6	19.0	21.5			17.6	20.9	18.4			21.6
171-180	32.3	33.9			31.3	21.1	23.1			20.2	21.5	20.9			17.6
321-330				26.1					15.8						14.0
331-340				25.4					14.8						16.2
341-350				26.0					15.0						14.7
351-360				25.5					14.8						17.3
361-365				25.5					13.8						20.7
Seasonal Average	31.0	30.3	25.7	27.4	28.6	17.3	15.9	13.5	16.1	15.6	18.6	20.6	18.4	16.4	18.9

Table B-3 Overview of weather data (fall) for Bradenton 1995 (B-95), Immokalee 1995 (I-95), and Quincy 1995 (Q-95).

Period	Tmax (°C)			Tmin (°C)			Total Radiation (MJ $m^{-2}d^{-1}$)		
(Julian dates)	B-95	I-95	Q-95	B-95	I-95	Q-95	B-95	I-95	Q-95
201-210			33.7			22.4			15.8
211-220			32.1			21.9			17.8
221-230			34.1			23.9			14.3
231-240			32.7			22.8			14.9
241-250			32.2			20.2			17.2
251-260			31.7			20.6			13.0
261-270	33.9		29.9	22.9		18.4	16.0		12.5
271-280	32.4		29.1	23.3		19.7	11.7		11.5
281-290	31.3		26.1	22.0		15.9	12.3		9.2
291-300	29.7	31.4		19.2	23.4		12.1	19.3	
301-310	29.5	29.8		18.3	22.9		12.7	17.5	
311-320	24.0	29.9		11.4	21.1		13.4	13.5	
321-330	23.2	29.8		10.2	19.0		12.7	19.8	
331-340	25.9	25.1		12.8	12.1		12.4	22.0	
341-350	25.1	24.6		11.2	11.1		11.6	20.8	
351-360	19.5	26.4		8.9	13.0		8.8	19.4	
361-365	18.2	19.8		7.6	9.3		8.5	11.2	
1-10			21.4		8.6			16.7	
11-20			22.8		8.1			17.0	
21-30			25.7		13.2			18.4	
Seasonal Average	27.9	26.1	31.3	16.7	14.7	20.7	12.5	17.8	14.0

Table B-4. Soil characteristics for an Eaugallie fine sand (sandy, siliceous, hyperthermic, alfic Haplaquods) [6]

Depth	Horizon	Water content (Vol. %)			Ks [4]	Bulk dens.	Org. C	Part. size dist. (%)			pH [5]	C.E.C.
(cm)	design.	P.W.P [1]	F.C. [2]	Sat. [3]	(cm hr^{-1})	(g cm^{-3})	(%)	sand	silt	clay		(cmol^{+} kg^{-1})
0- 18	Ap	2.2	13.3	42.3	18.4	1.22	1.02	98.1	1.1	0.8	6.0	3.9
18- 36	E1	2.2	11.1	43.0	15.8	1.51	0.70	96.5	2.9	0.6	5.0	2.6
36- 74	E2	1.6	8.1	38.9	21.1	1.62	0.14	97.5	1.9	0.6	4.8	0.2
74- 81	Bh1	3.5	24.8	39.6	22.4	1.60	1.20	91.5	4.8	3.7	4.5	8.1
81-119	Bh2	1.3	15.9	37.4	12.4	1.66	0.60	95.9	2.6	1.5	4.8	2.8
119-173	Bw	2.8	25.2	37.4	7.1	1.66	0.53	94.7	2.9	2.4	4.9	4.1
173-190	Btg1	7.0	26.0	32.4	0.5	1.79	0.21	84.0	3.0	13.0	4.8	5.7
190-203	Btg2	13.4	28.3	29.4	0.1	1.87	0.14	76.1	2.1	21.8	4.2	6.7

Table B-5. Soil characteristics for an Immokalee fine sand (sandy, siliceous, hyperthermic, arenic Haplaquods) [6]

Depth	Horizon	Water content (Vol. %)			Ks [4]	Bulk dens.	Org. C	Part. size dist. (%)			pH [5]	C.E.C.
(cm)	design.	P.W.P [1]	F.C. [2]	Sat. [3]	(cm hr^{-1})	(g cm^{-3})	(%)	sand	silt	clay		(cmol^{+} kg^{-1})
0- 10	Ap	3.4	9.2	48.7	28.4	1.36	1.02	99.2	0.2	0.6	5.1	15.0
10- 36	E1	2.9	5.9	43.0	30.9	1.51	0.15	99.0	0.6	0.4	5.1	1.3
36- 79	E2	2.0	5.7	46.0	35.0	1.43	0.02	97.5	0.3	0.3	5.7	0.3
79- 99	Bh11	2.4	15.8	40.8	6.6	1.57	1.01	97.2	1.1	1.4	5.3	14.6
99-112	Bh12	1.7	11.7	40.4	7.8	1.58	0.60	94.7	1.1	1.7	5.6	13.3
112-117	Bh2	3.6	22.3	38.5	0.3	1.63	1.89	93.7	1.5	4.8	5.3	18.4
117-155	B3	1.4	8.6	40.8	17.4	1.57	0.63	96.7	0.7	2.6	6.0	13.4
155-203	C	1.4	8.6	40.8	17.4	1.57	0.67	97.4	0.4	2.2	4.6	13.6

Table B-6. Soil characteristics of a Millhopper fine sand (loamy, siliceous, hyperthermic, Grossenic Paleudults) [7]

Depth	Horizon	Water content (Vol. %)			Ks [4]	Bulk dens.	Org. C	Part. size dist. (%)			pH [5]	C.E.C.
(cm)	design.	P.W.P [1]	F.C. [2]	Sat. [3]	(cm hr^{-1})	(g cm^{-3})	(%)	sand	silt	clay		(cmol^{+} kg^{-1})
0- 15	Ap	2.4	16.1	48.7	9.3	1.36	0.73	91.6	6.3	2.1	5.2	5.4
15- 33	E1	1.6	10.4	40.7	24.4	1.55	0.34	93.6	4.1	2.3	5.4	2.9
33- 89	E2	1.1	11.3	40.8	31.9	1.57	0.19	94.3	3.3	2.4	5.2	1.9
89-147	E3	2.1	8.0	38.5	32.9	1.63	0.07	94.8	3.3	1.9	5.3	1.1
147-157	Bw	2.2	10.1	40.4	19.8	1.58	0.07	92.0	3.9	4.1	5.2	2.0
157-175	Bt1	7.0	19.6	37.4	4.0	1.66	0.10	77.5	6.1	16.4	4.9	6.0
175-203	Bt2	10.5	24.8	35.1	0.9	1.72	0.12	62.8	8.6	28.6	5.0	10.4

[1] "Permanent wilting point": 15.0 bar
[2] "Field capacity": 0.1 bar
[3] "Saturation": 0.0035 bar
[4] Ks: saturated hydraulic conductivity
[5] pH of 1:1 H_2O extract
[6] Source: Carlisle et al., 1985
[7] Source: Carlisle et al., 1988

Table B-7. Soil characteristics of an Orangeburg loamy sand (fine-loamy, siliceous, hyperthermic, typic Paleudults) [7]

Depth	Horizon	Water content (Vol. %)			Ks [5]	Bulk dens.	Org. C	Part. size dist. (%)			pH [6]	C.E.C.
(cm)	design.	P.W.P [1]	F.C. [2]	Sat. [4]	(cm hr^{-1})	(g cm^{-3})	(%)	sand	silt	clay		(cmol^{+} kg^{-1})
0- 15	A	7.3	21.0	46.8	4.8	1.41	1.02	83.4	6.6	10.0	6.0	11.6
15- 38	E	6.8	18.2	46.8	13.0	1.41	0.71	80.6	9.6	9.8	5.1	9.5
38- 66	Bt1	8.1	18.2	41.1	4.8	1.56	0.29	79.8	6.0	14.2	4.9	7.0
66-112	Bt21	15.3	28.7	37.7	0.4	1.65	0.10	67.8	4.8	27.4	5.0	8.2
112-157	Bt22	13.4	26.7	39.6	0.7	1.60	0.12	63.6	4.2	32.2	4.7	9.8
157-203	Bt23	16.4	29.4	37.4	0.3	1.66	0.09	65.0	4.9	30.1	4.7	9.0

Table B-8 Soil characteristics of an Coto clay (clayey, kaolinitic, isohyperthermic, inceptic, Hapludoxes) [8]

Depth	Horizon	Water content (Vol. %)			Ks [5]	Bulk dens.	Org. C	Part. size dist. (%)			pH [6]	C.E.C.
(cm)	design.	P.W.P [1]	F.C. [3]	Sat. [4]	(cm hr^{-1})	(g cm^{-3})	(%)	sand	silt	clay		(cmol^{+} kg^{-1})
0- 23	Ap	20.0	26.9	43.4	--	1.35	2.75	31.0	7.9	61.1	5.5	11.6
18- 36	B21	21.6	26.7	45.8	--	1.40	1.37	27.4	6.0	66.6	4.9	7.5
36- 74	B22	23.0	27.5	47.4	--	1.36	0.84	24.3	5.3	70.4	4.8	5.8
74- 81	B23	24.7	35.2	48.4	--	1.19	0.57	22.5	5.0	72.5	5.0	5.6
81-119	B24	25.2	32.7	49.1	--	1.17	0.41	20.0	5.8	74.2	5.3	5.5
119-173	B25	22.6	25.3	47.4	--	1.54	0.22	20.8	9.3	69.9	5.3	4.6
173-190	B26	20.5	25.2	42.2	--	1.55	0.17	29.1	13.1	57.8	5.0	4.0
190-203	B27	24.7	31.0	41.7	--	1.55	0.18	25.8	18.1	56.1	4.7	4.8

[1] "Permanent wilting point": 15.0 bar
[2] "Field capacity": 0.1 bar
[3] "Field capacity": 0.3 bar
[4] "Saturation": 0.0035 bar
[5] Ks: saturated hydraulic conductivity
[6] pH of 1:1 H_2O extract
[7] Source: Carlisle et al., 1985
[8] Source: F.F. Beinroth 1995

APPENDIX C
INPUT FILES USED FOR THE TOMGRO MODEL

Table C-1. CROPPARM.TOM original input file parameter listing

0.33 20 20 10.E-12 0.700 1.00 1.00	TPL,NL,NF,EPS,GREF,SPTEL,GENFAC
5.00 0.200 06.0 1.4 0.015 0.010 12.0	XLAIM,XMRDR,ABORMX,Q10,RMRL,RMRF,FTRUSN
0.1 0.0 .075 .024 .075 4.0	WPLI,WPFI,SLAMX,SLAMN,STDSLA(m2/g),FRLG
0.00030 30.0 10.0 0.40 0.50	SCO2,THIGH,TLOW,TTMX,TTMN
10. 20. 30. 40. 50. 60. 70. 80. 90. 100.	BOX(I), I=1,10
.0006 .0015 .0026 .0029 .0029 .0029 .0029 .0029 .0025 .0000 .000	POL(I), I=1,10
0.03 0.07 0.10 0.13 0.27 0.27 0.27 0.27 0.1 0.0	POF(I), I=1,10
1.0 1.0 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00	ASLA(I), I=1,10
.49 .49 .49 .49 .49 .49 .49 .49 .49 .49	FRPET(I),I=1,10
.33 .33 .33 .33 .33 .33 .33 .33 .33 .33	FRSTEM(I),I=1,10
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0	DIS(I),I=1,10
0.0 0.0 1.0 1.0 1.0 1.0 0.0 0.0	PGRED(I),I=1,8
-10. -2.0 12.0 20.0 28.0 33.0 45.0 80.0	TMPG(I),I=1,8
0.0 0.0 0.5 1.0 2.0 3.0 3.5 3.5 3.5 3.5	FPN TABLE
-40. 0.0 1.0 2.0 3.0 9.0 15.0 24.0 50.0 90.0	XFPN VALUES
0.0 0.0 0.55 1.0 0.0 0.0	GENTEM TABLE
0.0 8.0 12.0 30.0 50.0 80.0	XTEM VALUES, DEG C
0.50 0.50 0.50 0.50 0.50 0.50	GENRAT TABLE, NODES/DAY
0.0 10.0 20.0 30.0 40.0 90.0	XGEN PLSTN OR NODES DEV
0.0 0.0 .0048 .0063 .0095 .0130 .0130 0.0 0.0	RDVLVT TABLE, VEG DEV R
0.0 9.0 12.0 15.0 21.0 28.0 35.0 50.0 80.0	XLV, TEMP VALUES, DEG C
0.0 0.0 .0053 .0103 .0203 .0320 .0320 0.0 0.0	RDVFRT TABLE, FR DEV RA
0.0 9.0 12.0 15.0 21.0 28.0 35.0 50.0 80.0	XFRT, TEMP VALUES, DEG
0.2 0.15 0.10 0.07 0.07 0.07	PROOT TABLE, FRACTION
1.0 12.0 20.0 30.0 50.0 90.0	XROOT, PLSTN OR VEG NOD
5.0 5.0 6.0 6.8 8.0 10.0	DMC84T TABLE, G FW/G DW
0.0 50.0 100. 150. 200. 250.	XDMC, DAYS

Table C-2. CROPPARM.TOM modified input file parameter listing

0.33 20 20 10.E-12 0.700 1.00 1.00	TPL,NL,NF,EPS,GREF,SPTEL,GENFAC
5.00 0.200 06.0 1.4 0.015 0.010 12.0	XLAIM,XMRDR,ABORMX,Q10,RMRL,RMRF,FTRUSN
0.1 0.0 .040[1] .020 .034 4.0	WPLI,WPFI,SLAMX,SLAMN,STDSLA(m2/g),FRLG
0.00030 30.0 10.0 0.40 0.50	SCO2,THIGH,TLOW,TTMX,TTMN
10. 20. 30. 40. 50. 60. 70. 80. 90. 100.	BOX(I), I=1,10
.0012 .0030 .0052 .0058 .0058 .0058 .0058 .0050 .0000 .000	POL(I), I=1,10
0.03 0.07 0.10 0.13 0.27 0.27 0.27 0.27 0.1 0.0	POF(I), I=1,10
1.0 1.0 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00	ASLA(I), I=1,10
.49 .49 .49 .49 .49 .49 .49 .49 .49 .49	FRPET(I),I=1,10
.33 .33 .33 .33 .33 .33 .33 .33 .33 .33	FRSTEM(I),I=1,10
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0	DIS(I),I=1,10
0.0 0.0 1.0 1.0 1.0 1.0 0.0 0.0	PGRED(I),I=1,8
-10. -2.0 12.0 20.0 28.0 33.0 45.0 80.0	TMPG(I),I=1,8
0.0 0.0 0.5 1.0 2.0 3.0 3.5 3.5 3.5 3.5	FPN TABLE
-40. 0.0 1.0 2.0 3.0 9.0 15.0 24.0 50.0 90.0	XFPN VALUES
0.0 0.0 0.55 1.0 0.0 0.0	GENTEM TABLE
0.0 8.0 12.0 30.0 50.0 80.0	XTEM VALUES, DEG C
0.50 2.00 10.0 10.0 10.0 10.0 1.0	GENRAT TABLE, NODES/DAY
0.0 10.0 20.0 30.0 40.0 90.0 200.0	XGEN PLSTN OR NODES DEV
0.0 0.0 .0144 .0189 .0285 .0390 .0390 0.0 0.0	RDVLVT TABLE, VEG DEV R
0.0 9.0 12.0 15.0 21.0 28.0 35.0 50.0 80.0	XLV, TEMP VALUES, DEG C
0.0 0.0 .0053 .0103 .0203 .0320 .0320 0.0 0.0	RDVFRT TABLE, FR DEV RA
0.0 9.0 12.0 15.0 21.0 28.0 35.0 50.0 80.0	XFRT, TEMP VALUES, DEG
0.2 0.15 0.10 0.07 0.07 0.07	PROOT TABLE, FRACTION
1.0 12.0 20.0 30.0 50.0 90.0	XROOT, PLSTN OR VEG NOD
5.0 5.0 6.0 6.8 8.0 10.0	DMC84T TABLE, G FW/G DW
0.0 50.0 100. 150. 200. 250.	XDMC, DAYS

[1] modified parameters are underlined

Table C-3. CROPPARM.TOM modified input file parameter listing (branching version of TOMGRO)

0.5[1] 20 20 10.E-12 0.700 1.00 1.00	TPL,NL,NF,EPS,GREF,SPTEL,GENFAC
5.00 0.200 06.0 1.4 0.015 0.01 6.0	XLAIM,XMRDR,ABORMX,Q10,RMRL,RMRF,FTRUSN
0.1 0.0 .040 .020 .034 4.0	WPLI,WPFI,SLAMX,SLAMN,SIDSLA(m2/g),FRLG
0.00030 30.0 10.0 0.40 0.50 1.0 60.0	SCO2,THIGH,TLOW,TTMX,TTMN,NBR,BRMAX
10. 20. 30. 40. 50. 60. 70. 80. 90. 100.	BOX(I), I=1,10
.0012 .0030 .0052 .0058 .0058 .0058 .0058 .0050 .0000 .000	POL(I), I=1,10
0.04 0.10 0.16 0.2 0.4 0.4 0.4 0.2 0.0	POF(I), I=1,10
1.0 1.0 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00	ASLA(I), I=1,10
.33 .33 .33 .33 .33 .33 .33 .33 .33 .33	FRPET(I),I=1,10
.33 .33 .33 .33 .33 .33 .33 .33 .33 .33	FRSTEM(I),I=1,10
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0	DIS(I),I=1,10
0.0 0.0 1.0 1.0 1.0 1.0 0.0 0.0	PGRED(I),I=1,8
-10. -2.0 12.0 20.0 28.0 33.0 45.0 80.0	TMPG(I),I=1,8
0.0 0.0 0.5 1.0 2.0 3.0 1.5 0.0 0.0 0.0	FPN TABLE
-40. 0.0 1.0 2.0 3.0 9.0 15.0 20.0 25.0 90.0	XFPN VALUES
0.0 0.0 0.55 1.0 0.0 0.0	GENTEM TABLE
0.0 8.0 12.0 30.0 50.0 80.0	XTEM VALUES, DEG C
0.50 0.50 0.50 0.50 0.50 0.50	GENRAT TABLE, NODES/DAY
0.0 10.0 20.0 30.0 40.0 90.0	XGEN PLSTN OR NODES DEV
0.0 0.0 .0144 .0189 .0315 .0390 .0390 0.0 0.0	RDVLVT TABLE, VEG DEV R
0.0 9.0 12.0 15.0 21.0 28.0 35.0 50.0 80.0	XLV, TEMP VALUES, DEG C
0.0 0.0 .0053 .0103 .0203 .0320 .0320 0.0 0.0	RDVFRT TABLE, FR DEV RA
0.0 9.0 12.0 15.0 21.0 28.0 35.0 50.0 80.0	XFRT, TEMP VALUES, DEG
0.2 0.15 0.10 0.07 0.07 0.07	PROOTTABLE, FRACTION
1.0 12.0 20.0 30.0 50.0 90.0	XROOT, PLSTN OR VEG NOD
5.0 5.0 6.0 6.8 8.0 10.0	DMC84T TABLE, G FW/G DW
0.0 50.0 100. 150. 200. 250.	XDMC, DAYS

[1] modified parameters are underlined

APPENDIX D
INPUT FILES USED FOR THE CROPGRO MODEL

Table-1. Modified TMGRO940.SPE file (July 1996 version)

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*TOMATO SPECIES COEFICIENTS - CRGRO940 MODEL

*PHOTOSYNTHESIS PARAMETERS
25.91 75.54 0.60 [1]                    PARMAX,PHTMAX,KCAN
80.0   2.09 .0105                       CCMP,CCMAX,CCEFF; CO2 EFFECT ON PGCAN
2.30  4.00 20.0 20.0  QDR               FNPGN(4),TYPPGN-LEAF N EFFECT ON PG
5.00 27.0 34.0 48.0  LIN                FNPGT(4),TYPPGT-TEMP EFFECT-CANOPY PG
0.0  5.0 25.0  28.0 34.0  48.0          XLMAXT (6 VALUES)
0.0  0.0  0.9  1.0  1.0   0.0           XLMAXT (6 VALUES)
1.00 14.00 50.0 60.0  QDR               FNPGL(4),TYPPGL-TMIN EFFECT-LEAF PG
.0541 0.20 0.80  2.0                    PGEFF SCV KDIF, LFANGB
.0045 .0006 .2500  4.76 1.36            SLWREF,SLWSLO,NSLOPE,LNREF,PGREF
0.0 .001  .002  .003 .0035  .004  .005  .006  .008  .010      XPGSLW(1-10)
.162  .679  .867  .966 1.000 1.027 1.069 1.100 1.141 1.167    YPGSLW(1-10)

*RESPIRATION PARAMETERS
3.5E-04 .0030                           RES30C,R30C2
2.478 2.478  .280  2.478                RNO3C,RNH4C,RPRO,RFIXN
1.242 3.106 2.174  .929  0.05  1.13     RCH20,RLIP,RLIG,ROA,RMIN,PCH2O

*PLANT COMPOSITION VALUES
.370  .220  .154  .256  .156  .112      PROLFI,PROLFG,PROLFF,PROSTI,PROSTG,PROSTF
.144  .119  .060  .245  .110  .100      PRORTI,PRORTG,PRORTF,PROSHI,PROSHG,PROSHF
.300  .300  .119                        SDPROS,SDPROG,PRONOD
.430  .674  .641  .442  .125  .480      PCARLF,PCARST,PCARRT,PCARSH,PCARSD,PCARNO
.025  .020  .020  .020  .510  .050      PLIPLF,PLIPST,PLIPRT,PLIPSH,PLIPSD,PLIPNO
.070  .070  .070  .280  .020  .070      PLIGLF,PLIGST,PLIGRT,PLIGSH,PLIGSD,PLIGNO
.050  .050  .050  .040  .040  .050      POALF,POAST,POART,POASH,POASD,POANO
.094  .046  .057  .030  .025  .050      PMINLF,PMINST,PMINRT,PMINSH,PMINSD,PMINNO

*CARBON AND NITROGEN MINING PARAMETERS
0.015 0.70  .250  .060 0.40  0.15       CMOBMX,CADSTF,CADPR1,NMOBMX,NVSMOB,NRCVR
0.04  0.08  0.04  0.08                  ALPHL,ALPHS,ALPHR,ALPHSH

*NITROGEN FIXATION PARAMETERS
.045  .160  0.01  0.0  0.04  0.05       SNACTM,NODRGM,DWNODI,TTFIX,NDTHMX,CNODCR
7.00 28.0 35.0 44.0  LIN                FNNGT(4),TYPNGT-TEMP EFF ON NOD GROWTH
5.00 23.0 35.0 44.0  LIN                FNFXT(4),TYPFXT-TEMP EFF ON N FIX
0.00 0.20 1.00 10.0  LIN                FNFXD(4),TYPFXD-REL SW-DRY EFF ON N FIX
0.00 0.02 1.00 2.00  LIN                FNFXW(4),TYPFXW-REL SW-WET EFF ON N FIX
0.00 0.10 1.00 0.00  INL                FNFXA(4),TYPFXA-AGE EFF ON N FIX

*VEGETATIVE PARTITIONING PARAMETERS
0.0  2.2  4.2  6.2  8.5  10.8  12.3  13.4  14.0  16.0      XLEAF VALUES
0.61 0.58 0.55 0.52 0.48 0.45 0.42 0.41 0.40 0.37        YLEAF VALUES
0.22 0.27 0.31 0.35 0.39 0.44 0.47 0.49 0.51 0.54        YSTEM VALUES
0.55 0.21 0.50 0.30 0.30                                 WTFSD,PORPT,FRSTMF,FRLFF,ATOP
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[1] modified parameters are underlined

```
*LEAF GROWTH PARAMETERS
 200  245  300  4.0  0.0                FINREF,SLAREF,SIZREF,VSSINK,EVMODC
 590. 270.0 -.047 1.50                   SLAMAX,SLAMIN,SLAPAR,TURSLA
 0.0  1.7  4.3  5.9  6.9  7.9            XVGROW(1-6), VSTAGE VALUES
 15.4  28.1  83.4 210.0 340.0 550.0     YVREF(1-6), LEAF AREA VALUES,CM2
 -50.0  00.0  15.0  26.0  60.0          XSLATM(1-5),TEMP VALUES
 0.48  0.48  0.48  1.00  1.0            YSLATM(1-5),EFFECT ON SLA

*LEAF SENESCENCE FACTORS
 1.00  0.00  0.02 -2.22 -5.00           SENRTE,SENRT2,SENDAY,FREEZ1,FREEZ2
 0.01  50.0                             ICMP,TCMP(Light comp, time constant-senes)
 .......XSTAGE.......  .......XSENMX.......
 0.0  5.0  14.0  30.0  3.0  5.0  10.0  30.0
 .......SENPOR.......  .......SENMAX.......
 0.0  0.0  0.12  0.16  0.0  0.4  0.5  0.5

*ROOT PARAMETERS
 10.0 7500  0.030  0.1  0.01  1.50  0.04
RTDEPI,RFACT,RTSEN,RLDSM,RTSDF,RWUEP1,RWUMX
 0.0  2.85  3.0  2.85  6.0  2.85  30.0  2.85          XRTFAC,YRTFAC
 0.006 0.006                            RTNO3,RTNH4

*SEED AND SHELL GROWTH PARAMETERS
 0.30  0.3  0.00  100.                  SETMAX,SRMAX,RFLWAB,XMPAGE
 15.0  0.0  0.0                         DSWBAR,XFRMAX,SHLAG
 17.0  21.0  26.5  40.0  QDR            FNPDT(1-4),TYPPDT-TEMP EFFECT ON POD SET
 6.0  21.0  23.5  41.0  QDR             FNSDT(1-4),TYPSDT-TEMP EFFECT ON SD GRWTH
 0.00 10.00 20.00 33.00 46.00 60.00     XXFTEM(1-6),TEMPERATURES
 0.00  1.00  1.00  1.00  0.40  0.40     YXFTEM(1-6),REL CHG IN PARTIT
 0.00  0.01  1.00  1.00                 XSWFAC(1-4)
 0.00  1.00  1.00  1.00                 YSWFAC(1-4)
 0.00  0.01  0.25  1.00  1.00           XSWBAR(1-5),REL WATER TOPSOIL
 0.00  0.00  1.00  1.00  1.00           YSWBAR(1-5),EFFECT ON PNUT PEGGING

*POD LOSS PARAMETERS
 N  6.0 .3961 -.865  3.405 0.102       DETACH,DWC,PR1DET,PR2DET,XP1DET,XP2DET

*PHENOLOGY PARAMETERS
 TB  TO1  TO2  TM        I
 11.0 28.0 28.0 55.0                    1 VEGETATIVE DEVELOPMENT
 11.0 28.0 28.0 55.0                    2 EARLY REPRODUCTIVE DEVELOPMENT
 11.0 28.0 28.0 55.0                    3 LATE REPRODUCTIVE DEVELOPMENT

FOLLOWING LINE: STAGE; REF STAGE; PHOTOPERIOD FUNCTION; TEMPERATURE FUNCT;
POINTER TO VEGD(1) OR REPDA(2) OR REPDB(3) TEMP SENS; SENS TO WATER;N; AND P
  1   1  NON  LIN    1 -0.50  0.00  0.00  PLANT(STG 1) TO EMERG(STG 2) PHASE
  2   2  NON  LIN    1 -0.50  0.00  0.00  EMERG(STG 2) TO V1(STG 3) PHASE
  3   2  NON  LIN    1 -0.50  0.00  0.00  EMERG(STG 2) TO END JV(STG 4) PHASE
  4   4  INL  SIN      1 -0.50  0.00  0.00  END JV(STG 4) TO FL IND(STG 5) PHASE
  5   5  INL  SIN    1 -0.50  0.00  0.00  FL IND(STG 5) TO 1ST FL(STG 6) PHASE
  6   6  INL  SIN    1 -0.50  0.00  0.00  1ST FL(STG 6) TO 1ST PEG(STG 7) PHASE
  7   6  INL  SIN    1 -0.50  0.00  0.00  1ST FL(STG 6) TO 1ST POD(STG 8) PHASE
  8   6  INL  SIN    1 -0.50  0.00  0.00  1ST FL(STG 6) TO 1ST SD(STG 9) PHASE
  9   9  INL  SIN    1  1.00  0.00  0.00  1ST SD(STG 9) TO LST SD(STG 10) PHASE
 10   9  INL  SIN    1  1.00  0.00  0.00  1ST SD(STG 9) TO PH MAT(STG 11) PHASE
 11  11  NON  NON    1  0.00  0.00  0.00  PH MAT(STG 11) TO H-MAT(STG 12) PHASE
 12   6  INL  SIN    1 -0.50  0.00  0.00  1ST FL(STG 6) TO LST VST(STG 13) PHASE
 13   6  INL  SIN    1 -0.50  0.00  0.00  1ST FL(STG 6) TO LST LF(STG 14) PHASE

*CANOPY HEIGHT AND WIDTH GROWTH PARAMETERS
 VSTAGE, FOLLOWED BY INTERNODE LENGTH PER NODE, THEN CANOPY WIDTH PER NODE
 0.00  0.85  3.02  7.02 11.48 13.82 14.00 16.00 20.00 40.00     XVSHT(1-10)
 0300 .0300 .0400 .0600 .1200 .1200 .1200 .1000 .0400 .0150  YVSHT(1-10)
 0300 .0300 .0500 .0700 .0900 .1000 .0600 .0300 .0200 .0100  YVSWH(1-10)
 -50.0  00.0  11.0  26.0  60.0                                XHWTEM(1-5),TEMPERATURES
 0.05  0.05  0.40  1.00  1.00                                YHWTEM(1-5),RELATIVE EXPAN
 0.00  5.00  7.50 10.00 15.00 20.00 30.00 80.00              XHWPAR(1-8),PAR VALUES
 4.00  2.00  1.50  1.25  1.05  1.00  1.00  1.00                    YHWPAR(1-8),RELATIVE EXPAN
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Table D-2. Overview of modifications in the cultivar parameter file (TMGRO940.CUL file)

*TOMATO GENOTYPE COEFFICIENTS - CRGRO940 MODEL

@VAR#	VRNAME.....	ECO#	CSDL	PPSEN	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	SLAVR	SIZLF	XFRT	WTPSD	SFDUR	SDPDV	PODUR
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TM0001	FLOR. ORG. PEAN.	TM0001	11.84	0.00	18.4	7.0	18.0	83.70	73.20	1.36	280.	20.0	0.95	0.570	36.0	1.70	42.0
TM0002	INIT. DET. TOM.	TM0002	12.33	0.00	20.0	11.0	17.0	50.00	60.00	1.10	310.	300.0	0.70	0.010	35.0	19.99	90.0
TM0003	INIT. IND. TOM.	TM0003	12.33	0.00	20.0	11.0	17.0	50.00	60.00	1.10	280.	300.0	0.70	0.010	35.0	19.99	45.0
TM0004	FIT. DET. TOM.	TM0004	12.33	0.00	20.0	11.0	17.0	50.00	60.00	1.18	335.	300.0	0.95	0.010	35.0	19.99	35.0
TM0005	FIT. S-D. TOM.	TM0005	12.33	0.00	20.0	11.0	17.0	50.00	60.00	1.18	340.	300.0	0.77	0.010	35.0	19.99	42.0
TM0006	FIT. S-D. TOM.	TM0005	12.33	0.00	20.0	8.0	17.0	50.00	60.00	1.36	350.	300.0	0.77	0.004	35.0	250.0	42.0
TM0007	FIT. IND. TOM.	TM0009	12.33	0.00	20.0	11.0	17.0	50.00	60.00	1.18	350.	300.0	0.60	0.004	35.0	250.0	90.0

Definitions:

TM0001	Original peanut parameters for the peanut cultivar florunner
TM0002	Parameters used for 'sunny' tomato (October 1993 modifications)
TM0003	Parameters used for a generic indeterminate variety (October 1993 modifications)
TM0004	Parameters used for 'sunny' tomato (October 1993 modifications)
TM0005	Parameters used for 'sunny' tomato, a semi-determinate variety (October 1994 modifications)
TM0006	Parameters used for 'sunny' tomato (July 1996 modifications)
TM0007	Parameters used for a generic indeterminate variety (October 1994 modifications)
TM0002	Parameters used for 'sunny' tomato (October 1993 modifications)
TM0003	Parameters used for a generic indeterminate variety (October 1993 modifications)
ECO#	Code for the ecotype to which this cultivar belongs
CSDL	Critical Short Day Length below which reproductive development progresses with no daylength effect (h)
PPSEN	Slope of the relative response of development to photoperiod with time (h^{-1})
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)
FI-SH	Time between first flower and first pod (R3) (photothermal days)
FI-SD	Time between first flower and first seed (R5) (photothermal days)
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)
FI-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light ($CO2 m^{-2} s^{-1}$)
SLAVR	Specific leaf area of cultivar under standard growth conditions ($cm2 g^{-1}$)
SIZLF	Maximum size of full leaf (three leaflets) (cm2)
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD	Maximum weight per seed (g)
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)
SDPDV	Average seed per pod under standard growing conditions (#/pod)
PODUR	Time required for cultivar to reach final pod load under optimal

Table D-3. Overview of modifications in the ecotype parameter file (TMGRO940.CUL)

*TOMATO ECOTYPE COEFFICIENTS - CRGRO940 MODEL

@ECO#	ECONAME.....	MG	TM	PP-SS	PL-EM	EM-V1	V1-JU	JU-R0	PM06	PM09	LNHSH	R7-R8	FL-VS	TRIFL	RWDTH	RHGHT	THRSH	SDPRO	R1PPO
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
TM0001	FLOR. ORG. PEAN.	00	01	0.0	5.0	3.3	0.0	15.1	0.54	1.00	20.0	0.0	65.00	0.39	1.0	1.0	80.0	.280	.500
TM0002	INIT. DET. TOM.	01	01	0.0	1.0	1.0	0.0	00.0	0.0	0.75	35.0	0.0	60.00	0.45	1.0	1.0	4.0	.300	.000
TM0003	INIT. IND. TOM.	02	01	0.0	1.0	1.0	0.0	00.0	0.0	0.75	35.0	0.0	60.00	0.35	1.0	1.0	4.0	.300	.000
TM0004	FIT. DET. TOM.	00	01	0.0	0.0	0.0	0.0	00.0	0.0	1.00	35.0	0.0	60.00	0.40	1.0	1.0	4.0	.300	.000
TM0005	FIT. S-D. TOM.	01	01	0.0	0.0	0.0	0.0	00.0	0.0	0.75	35.0	0.0	60.00	0.45	1.0	1.0	4.0	.300	.000
TM0006	FIT. S-D. TOM.	01	01	0.0	0.0	0.0	0.0	00.0	0.0	0.75	35.0	0.0	60.00	0.52	1.0	1.0	9.2	.300	.000
TM0007	FIT. IND. TOM.	02	01	0.0	0.0	0.0	0.0	00.0	0.0	0.60	35.0	0.0	60.00	0.52	1.0	1.0	4.0	.300	.000

Definitions:

TM0001 Original peanut parameters for the peanut cultivar florunner
TM0002 Parameters used for 'sunny' tomato (October 1993 modifications)
TM0003 Parameters used for a generic indeterminate variety (October 1993 modifications)
TM0004 Parameters used for 'sunny' tomato (October 1993 modifications)
TM0005 Parameters used for 'sunny' tomato, a semi-determinate variety (October 1994 modifications)
TM0006 Parameters used for 'sunny' tomato (July 1996 modifications)
TM0007 Parameters used for a generic indeterminate variety (October 1994 modifications)
TM0002 Parameters used for 'sunny' tomato (October 1993 modifications)
IM0003 Parameters used for a generic indeterminate variety (October 1993 modifications)
PP-SS Minimum rate of reproductive growth under long days and optimal temperatures
PL-EM Time required for seed germination (thermal days)
EM-V1 Time required from emergence to the first true leaf stage (V1) (thermal days)
EM-JU Time required from emergence to the end of the juvenile phase (thermal days)
JU-RO Time required for floral induction (photothermal days)
PMO6 Proportion of time between first pod and first seed
PMO9 Proportion of time between first seed and physiological maturity
LNGSH Time required for shell growth (photothermal days)
R7-R8 Time between physiological maturity date and harvest maturity date (thermal time)
FL-VS Time from the appearnce of the first flower cluster to the last leaf on the main stem (photothermal time)
TRIFL Rate of appearance of leaves on the main stem (leaves per thermal day)
RWDTH Relative canopy width of this ecotype in comparison to the standard width as defined in the .SPE file
RHGTH Relative canopy height of this ecotype in comparison to the standard height as defined in the .SPE file
TRESH The maximum ratio of seed/(seed+shell) at maturity
SDPRO Seed protein fraction (g protein per g seed)

BIBLOGRAPHY

Abdellatif, A. M., I.H. El-Sokkary, and T.C. Tucker. 1987. Growth and chlorophyll, mineral, and total amino acid composition of tomato and wheat plants in relation to nitrogen and iron nutrition. I. Growth and nutrient uptake. J. Plant Nutrition 10:699-712.

Acock, B., D.A. Charles-Edwards, D.J. Fitter, D.W. Hand, L.J. Ludwig, J. Warren Wilson, and A.C. Withers. 1978. The contribution of leaves from different levels within a tomato canopy to net photosynthesis: An experimental examination of two canopy models. J. Exp. Bot. 29:815-827.

Adams, P. and A.M. El-Gizawy. 1986. Effect of salinity and watering level on the calcium content of tomato fruit. Acta Horticulturae 190:253-259.

Adams, P., G.W. Winsor, and J.D. Donald. 1973. The effects of nitrogen, potassium and sub-irrigation on the yield, quality and composition of single-truss tomatoes. J. Hort. Sci. 48:123-133.

Alvino, A., R. d'Andria, and G. Zerbi. 1988. Fruit ripening of different tomato cultivars as influenced by irrigation regime and time of harvesting. Acta Horticulturae 228:137-146.

Augustine, J.J., M.A. Stevens, and R.W. Breidenbach. 1979. Physiological, morphological, and anatomical studies of tomato genotypes varying in carboxylation efficiency. J. Am. Soc. Hort. Sci. 104:338-341.

Babcock, B.A. 1992. The effects of uncertainty on optimal nitrogen application. Rev. Agric. Econ. 14:271-280.

Barber, S.A. 1984. Nitrogen. p. 179-200. In Barber S.A. Soil Nutrient Bioavailability, A Mechanistic Approach. Wiley-Interscience Publications, New York, NY.

Barber, S.A. and M. Silverbush. 1984. Plant root morphology and nutrient uptake. p. 65-87. In S.A. Barber and D.R. Bouldwin (eds.) Roots, Nutrient and Water Influx, and Plant Growth. Am. Soc. Agron. Special Publication No. 49, Soil Sci. Soc. Am. ,Crop Sci. Soc. Am., and Am. Soc. Agron., Madison, WI.

Bar-Yosef, B. and B. Sagiv. 1982. Response of tomatoes to N and water applied via a trickle irrigation system. I. Nitrogen. II. Water. Agron. J. 74:633-637; 637-639.

Bar-Yosef, B., C. Stammers, and B. Sagiv. 1980. Growth of trickle-irrigated tomato as related to rooting volume and uptake of N and water. Agron J. 72:815-822.

Batilani, A. and P. Mannini. 1994. Influence of water table depth on the yield and quality of processing tomatoes. Acta Horticulturae 376:295-298.

Bennett, J.M., T.R. Sinclair, L. Ma, and K.J. Boote. 1993. Single leaf carbon exchange and canopy radiation use efficiency of four peanut cultivars. Peanut Sci. 20:1-5.

Bertin, N. and C. Gary. 1993. Tomato fruit set: A case study for validation of the model, TOMGRO. Acta Horticulturae 328:185-193.

Bhella, H.S. 1988. Tomato response to trickle irrigation and black polyethylene mulch. J. Am. Soc. Hort. Sci. 113:543-546.

Biemond, T. 1989. A tomato growth model as part of a bio-economic model. Acta Horticulturae 260:285-293.

Boggess, W.G. 1994. Decentralized water allocation in Florida. Paper presented at the Intern. Conf. on Coordination and Decentralization in Water Resource Management, Rehovot, Israel, October 1994. 14 pp.

Bonczek, J.L. and B.L. McNeal. 1996. Specific-gravity effects on fertilizer leaching from surface sources to shallow water tables. Soil Sci. Soc. Am. J. 60:978-985.

Boote, K.J., J.M. Bennett, J.W. Jones, and H.E. Jowers. 1989. On-farm testing of peanut and soybean models in Florida. Am. Soc. Agric. Engr. (ASAE), Paper No. 894040.

Boote, K.J. and J.W. Jones. 1988. Applications of, and limitations to, crop growth simulation models to fit crops and cropping systems to semi-arid environments. p. 63-75. In F.R. Biddinger and C. Johanson (eds.). Drought Research Priorities for the Dryland Tropics. ICRISAT, Patancheru, India.

Boote, K.J., J.W. Jones, J.W. Mishoe, and G.G. Wilkerson. 1986. Modeling growth and yield of groundnut. p. 243-254. In Agrometeorology of Groundnut. ICRISAT, Patancheru, India.

Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. Potential use and limitations of crop models. Agron. J. 88:704-716.

Boote, K.J. and R.S. Loomis. 1991. The prediction of canopy assimilation p. 109-140. In Modeling Crop Photosynthesis - From Biochemistry to Canopy. Crop Sci. Soc. Am. Special Publication No. 19, Soil Sci.Soc.Am., Crop Sci. Soc. Am., and Am. Soc. Agron., Madison, WI.

Borin, M. 1990. Irrigation management of processing tomato and cucumber in environments with different water table depths. Acta Horticulturae 267:85-92.

Bottcher, A.B., K.L. Campbell, L.W. Miller, D.W. Sweeney, and S.J. Locascio. 1986. Field assessment of agricultural BMPs. Soil Crop Sci. Soc. Fla. Proc. 45:60-67.

Bryan, H.H., J.W. Strobel, and J.D. Dalton. 1967. Effects of plant population and fertilizer rates on tomato yields on Rockdale soil. Fla. State Hort. Soc. Proc. p. 149-156.

Bussieres, P. 1993. Potential dry matter and water import rates in the tomato fruit in relationship to fruit size. Ann. Bot. 72:63-72.

Bussieres, P. 1994. Simulation of potential changes in tomato fruit mass and dry matter content during the second phase of growth. Acta Horticulturae 376:291-294.

Bussieres, P. and Y. Dumas. 1992. An analysis scheme for modeling the function of a tomato canopy. Acta Horticulturae 301:171-176.

Calado, A.M. and Portas, C.M. 1987. Base-temperature and date of planting in processing tomatoes. Acta Horticulturae 200:185-193.

Camp, C.R., M.L. Robbins, and D.L. Karlen. 1989. Micro irrigation for fresh market tomatoes on a high-water-table soil in the Southeastern coastal plain. Trans. Am. Soc. Agric. Engr. (ASAE) 32:1582-1586.

Camp, C.R., M.L. Robbins, D.L. Karlen, and R.E. Sojka. 1991. Irrigation management for double-cropped fresh-market tomatoes on a high-water-table soil. Trans. Am. Soc. Agric. Engr. (ASAE) 34:2445-2452

Carlisle, V.W., M.E. Collins, F. Sodek, and L.C. Hammond. 1985. Characterization data for selected Florida soils 85-1, Univ. of Florida, Gainesville, FL.

Carlisle, V.W., M.E. Collins, F. Sodek, L.C. Hammond, and W.G. Harris. 1989. Characterization data for selected Florida soils 89-1, Univ. of Florida, Gainesville, FL.

Cavazza, L. 1988. Problems in irrigation at farm and field level. Acta Horticulturae 228:19-34.

Challa, H. 1989. Modelling for crop growth control. Acta Horticulturae 248:209-216.

Challa, H and E. Heuvelink. 1993. Economic evaluation of crop photosynthesis. Acta Horticulturae 328:219-228.

Clark, G.A, G.J. Hochmuth, E.A. Hanlon, C.D. Stanley, D.N. Maynard, and D.Z. Haman. 1989a. Water and fertilizer management of micro-irrigated tomato production on sandy soil in Southwest Florida. Gulf Coast Res. and Educ. Center Final Report, Univ. of Florida, Bradenton, FL. 55 pp.

Clark, G.A, D.N. Maynard, C.D. Stanley, G.J. Hochmuth, E.A. Hanlon, and D.Z. Haman. 1989b. Irrigation scheduling and management of micro-irrigated tomatoes. Florida Coop. Ext. Serv. Circ. 872, Univ. of Florida, Bradenton, FL. 12 pp.

Colson, J., D. Wallach, A. Bouniols, J.P. Denis, and J.W. Jones. 1995. Mean squared error of prediction by SOYGRO. Agron. J. 87:397-402.

Commodity Research Bureau. 1995. The CRB Commodity Yearbook. John Wiley and Sons, Inc., New York, NY., 314 pp.

Cooper, A.J. 1972. Partitioning of dry matter by the tomato. J. Hort. Sci. 47:137-140

Cooper, A. J. and J.H.M. Thornley. 1976. Response of dry matter partititioning, growth, and carbon and nitrogen levels in the tomato plant to the changes in root temperature: Experiment and theory. Ann. Bot. 40:1139-1152.

Csizinszky, A.A., J.B. Jones, C.D. Stanley, and S.P. Kovach. 1988. Effect of N and K rates on bacterial spot in trickle irrigated tomatoes. Proc. Fla. State Hort. Soc. 101:353-356.

Csizinszky, A.A. and D.J. Schuster. 1982. Yield response of staked, fresh-market tomatoes to reduced use of fertilizers and insecticides. J. Am. Soc. Hort. Sci. 107:648-652.

Dayan, E., H. van Keulen, J.W. Jones, I. Zipori, D. Shmuel, and H. Challa. 1993. Development, calibration and validation of a greenhouse tomato growth model: I. Description of the model. II. Field calibration and validation. Agric. Systems 43:145-163; 165-183.

Dirks, V.A. and C.S. Tan 1988. Root distribution of irrigated and non-irrigated vegetable crops. Acta. Horticulturae 228:299-305

Doorenbos, J. and A.H. Kassam 1986. Yield response to water. FAO Irrigation and Drainage Paper 33, FAO, Rome, Italy. 176 pp.

Doss, B.D., C.E. Evans, and W.A. Johnson. 1975. Rates of nitrogen and irrigation for tomatoes. J. Am. Soc. Hort. Sci. 100:435-437

Ehret, D.L and L.C. Ho. 1986. The effects of salinity on dry matter partitioning and fruit growth in tomatoes grown in nutrient film culture. J. Hort. Sci. 61:361-367.

Errebhi, M. and G.E. Wilcox. 1990. Tomato growth and nutrient uptake pattern as influenced by nitrogen form ratio. J. Plant Nutrit. 13:1031-1043.

Everett, P.H. 1976. Effect of nitrogen and potassium rates on fruit yield and size of mulch-grown staked tomatoes. Proc. Fla. State Hort. Soc. 89:159-162.

Fischer, H.H. and P.C. Nel. 1990. Deficit drip irrigation of market tomatoes on three soil types. Acta Horticulturae 27:797-805.

Florida Agricultural Statistics Service. 1995. Vegetable Summary 1993-1994. Florida Agric. Statistic Service, Orlando, FL.

Florida Agricultural Statistics Service. 1996. Vegetables, acreage, production and value. U.S. Department of Agriculture, Washington D.C. 2 pp.

Follett, R.F. and D.J. Walker. 1989. Groundwater quality concerns about nitrogen. p. 1-22. In R.F. Follett (ed.). Nitrogen Management and Groundwater Protection, Elsevier, Amsterdam, The Netherlands.

Food and Agricultural Organization. 1995. FAO Yearbook Production 1994 Vol. 48, FAO, Rome, Italy.

France, J. and J.H.M. Thornley. 1984. Mathematical Models in Agriculture. Butterworths, London, U.K.

Gasim. A. and R.G. Hurd. 1986. The root activity of fruiting tomato plants. Acta Horticulturae 190:267-279.

Gent, M.P.N. and H.Z. Enoch. 1983. Temperature dependence of vegetative growth and dark respiration: A mathematical model. Plant Phys. 71:562-567.

Gianquinto, G., P. Ceccon, and R. Giovanardi. 1990. Evapotranspiration, growth and yield of fresh market tomato (Lycopersicon esculentum Mill.) at two irrigation levels. Acta Horticulturae 278:579-586.

Giardini, L., R. Giovanardi, and M. Borin. 1988a. Water consumption and yield response of tomato in relation to water availability at different soil depths. Acta Horticulturae 228:119-126.

Giardini, L., R. Giovanardi, and M. Borin. 1988b. Soil moisture influence on the productivity of industry tomato grown in lysimeters. Acta Horticulturae 228:147-154.

Godwin, D.C. and C.A. Jones. 1989. Nitrogen dynamics in soil-plant systems. p 287-22. In J. Hanks and J.T. Ritchie (eds.). Modeling Plant and Soil Systems. Am. Soc. Agron. Series No. 31. Am. Soc. Agron. , Crop Sci. Soc. Am., and Soil Sci. Soc. Am., Madison, WI.

Gosselin, A., J. Charbonneau, L.P Vezina, and M.J. Trudel. 1988. Restrictions in vegetative growth of tomato plants imposed by altering the nitrogen concentration and electrical conductivity of the nutrient solution. Acta Horticulturae 222:71-78.

Goudriaan, J. and J.L. Monteith. 1990. A mathematical function for crop growth based on light interception and leaf area. Ann. Bot. 66:695-701

Goudriaan, J. and H.H. van Laar. 1994. Modelling Potential Crop Growth Processes Kluwer, Dordrecht, The Netherlands.

Greenwood, D.J. and A. Draycott. 1988. p. 46-61.Recovery of fertilizer-N in diverse vegetable crops. In D.S. Jenkinson and K.A. Smith (eds.). Nitrogen Efficiency in Agricultural Soils, Elsevier Applied Science, London, U.K..

Grierson, D. and A.A. Kader. 1986. Fruit ripening and quality. p. 241-280. In J.G. Atherton and J. Rudich (eds.) The Tomato Crop, A Scientific Basis for Improvement. Chapman and Hall, London, U.K..

Gulmon, S.L. and N.C. Turner. 1978. Differences in root and shoot development of tomato (Lycopersicon esculentum L.) varieties across contrasting soil environments. Plant and Soil 49:127-136.

Haen, H. de. 1990. Economic aspects of controlling the nitrate contamination of drinking water. Strategies, costs, and financing. p. 23-40. In Calvet, R. (ed.). Nitrate-Agriculture-Eau International Symposium Institute Nationale de la Researche Agronomique (INRA), Paris, France.

Heuvelink, E. and L.F. M. Marcelis. 1989. Dry matter distribution in tomato and cucumber. Acta Horticulturae 260:149-157.

Hewitt, J.D., M. Dinar, and M.A. Stevens. 1982. Sink strength of fruits of two tomato genotyes differing in total fruit solids contents. J. Am. Soc. Hort. Sci. 107:896-900.

Ho, L.C. 1975. The relationship between the rates of carbon transport and of photosynthesis in tomato leaves. J. Exp. Bot. 27:87-97.

Ho, L.C. 1988. The physiological basis for improving dry matter content and calcium status in tomato fruit. Appl. Agric. Res. 3:275-281.

Ho, L.C., R.I. Grange, and A.J. Picken. 1987. An analysis of the accumulation of water and dry matter in tomato fruit. Plant Cell Env. 10:157-162.

Ho, L.C. and J.D. Hewitt. 1986. Flowering p. 167-239; and Fruit development p. 201-239. In J.G. Atherton and J. Rudich (eds.) The Tomato Crop, A Scientific Basis for Improvement. Chapman and Hall, London, U.K..

Ho, L.C., A.F. Shaw, J.B.W. Hammond, and K.S. Burton. 1983. Source-sink relationships and carbon metabolism in tomato leaves. I. ^{14}C Assimilate compartmentation. Ann. Bot. 52:365-372.

Ho, L.C. , V. Shut, and G.V. Hoad. 1983. The effect of assimilate supply on fruit growth and hormone level. Plant Growth Regulation 1:155-171.

Hochmuth, G.J. 1988. Tomato Production Guide for Florida. Circular 98C, Florida Coop. Ext. Serv., Univ. of Florida, Gainesville, FL. 22 pp.

Hochmuth, G.J. (ed.) 1990. Nitrogen management in vegetable production for groundwater and health protection. Special Series Report SSVEC 940. Florida Coop. Ext. Serv., Univ. of Florida, Gainesville, FL. 35 pp.

Hochmuth, G.J. 1996 Evaluation of monopotassium phosphate-based starter fertilizer solution effects on vegetable production in Florida. Research Report, Horticultural Science Department, Univ. of Florida, Gainesville, FL. 24 pp.

Hochmuth, G.J., E.A. Hanlon, P. Gilreath, and K. Shuler. 1989. Field evaluations of nitrogen fertilization programs for subsurface-irrigated tomatoes. Proc. Fla. State Hort. Soc. 102:351-354.

Hochmuth, G.J., D. Maynard, C. Vavrina, and E.A. Hanlon. 1991. Plant tissue analysis and interpretation for vegetable crops in Florida. SS-VEC-42, Univ. of Florida, Gainesville, FL. 62 pp.

Hoogenboom, G., J.W. Jones, and K.J. Boote. 1992. Modeling growth, development, and yield of grain legumes using SOYGRO, PNUTGRO, and BEANGRO. A review. Trans. Am. Soc. Agric. Engr. (ASAE) 35:2043-2056.

Hsiao. T.C. 1981. Effects of water stress on crop plants. p.72-76. In D.W. Rains (ed.). A Congress on Biosalinity, Univ. of California, Davis, CA.

Hsiao, T.C. 1990. Plant-atmosphere interactions, evapotranspiration, and irrigation scheduling. Acta Horticulturae 278:55-66.

Huett, D.O. and E.B. Dettmann. 1988. Effect of nitrogen on growth, fruit quality and nutrient uptake of tomatoes grown in sand culture. Austr. J. Exp. Agric. 28:391-399.

Huett, D.O. and G. Rose.1988. Diagnostic nitrogen concentrations for tomatoes grown in sand culture. Austr. J. Exp. Agric. 28:401-409

Hurd, R.G. and J.H.M. Thornley. 1974. An analysis of the growth of young tomato plants in water culture at different light integrals and CO_2 concentrations. Ann. Bot. 38:375-388.

Jackson, L.E. and A.J. Bloom. 1990. Root distribution in relation to soil nitrogen availability in field-grown tomatoes. Plant and Soil 128:115-126.

Jaramillo, J.V., R.A. Munoz, F.P. Cardona. 1978. Respuesta del tomate (Lycopersicon esculentum Mill) a la fertilizacion con N, P, K y varios elementos menores, en suelos alluviales del valle del Cauca (Columbia). Revista ICA 13:455-464.

Johnson, B.S. and J.T. Ritchie. 1989. Simulation of soil water balance in IBSNAT crop models. Poster no. 102, IBSNAT Symposium, IBSNAT, Honolulu, HI.

Johnson, R.W., M.A. Dixon, and D.R. Lee. 1992. Water relations of the tomato during fruit growth. Plant Cell Env. 15:947-953.

Jones, J.P. 1979. Tolerance of tomato to manual defoliation. Proc. Fla. State Hort. Soc. 92:99-100.

Jones, J.W., K.J. Boote, S.S. Jagtap, and J.W Mishoe. 1991a. Soybean development p. 71-90. In J. Hanks and J.T. Ritchie (eds.). Modeling Plant and Soil Systems. Am. Soc. Agron. Series No. 31. Am. Soc. Agron., Crop Sci. Soc. Am., and Soil Sci. Soc. Am., Madison, WI.

Jones, J.W., E. Dayan, L.H. Allen, H. van Keulen, and H. Challa. 1989a. Modeling tomato growth for optimizing greenhouse temperatures and carbon dioxide concentrations. Acta Horticulturae 248:285-294.

Jones, J.W., E. Dayan, L.H. Allen, H. van Keulen, and H. Challa. 1991b. A dynamic tomato growth and yield model (TOMGRO). Trans. Am. Soc. Agric. Engr. (ASAE) 34:663-672.

Jones, J.W. , E. Dayan, P. Jones, I. Seginer, L.H. Allen, and I. Zipori. 1989b. On-line computer control system for greenhouses under high radiation and temperatures zones. Final report, BARD project US-871-74. Agric. Engr. Dept., Univ of Florida, Gainesville, FL. 300 pp.

Jones, J.W., L.A. Hunt., G. Hoogeboom, D.C. Godwin, U. Singh, G.Y. Tsuji, N.B. Pickering, P.K. Thornton, W.T. Bowen, K.J. Boote, and J.T. Ritchie. 1994. Input and output files. p. 1-94. In G.Y. Tsuji, G. Uehara, and S. Balas (eds.). Decision Support System for Agrotechnology Tranfer (DSSAT) Version 3, Volume 2. Univ. of Hawaii, Honolulu, HI.

Jones, J.W. and J.T. Ritchie. 1992. Crop growth models. p. 63-89. In G.J. Hoffman, T.A. Howell and K.H. Solomon (eds.). Management of Farm Irrigation Systems. Am. Soc. Agric. Engr. (ASAE), St. Joseph, MI.

Jury, W.A. and D.R. Nielsen. 1989. Nitrate transport and leaching mechanisms. p. 139-157. In R.F. Follett (ed.). Nitrogen Management and Groundwater Protection, Elsevier, Amsterdam, The Netherlands .

Kaniszewski, S., K. Elkner, and J. Rumpel. 1987. Effect of nitrogen fertilization and irrigation on yield, nitrogen staus and quality of direct seeded tomatoes. Acta Horticulturae 200:195-202.

Kano, A. and C.H.M. van Bavel. 1988. Design and test of a simulation model of tomato growth and yield in a greenhouse. J. Japan. Soc. Hort. Sci. 56:408-416.

Kebede, H., B. Martin, J. Nienhuis, and G. King. 1994. Leaf anatomy of two Lycopersicon species with contrasting gas exchange properties. Crop Sci. 34:108-113.

Keeney, D.R. and R.F. Follett. 1991. Managing nitrogen for groundwater quality and farm profitability: Overview and introduction. p. 1-7. In Follett, R.F., D.R. Keeney, and R.M. Cruse (eds.). Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Inc. Madison, WI.

Kenig, A., J.W. Mishoe, K.J. Boote, P.W. Cook, D.C. Reicosky, W.T. Pettigrew, and H.F. Hodges. 1993. Development of soybean fresh and dry weight relationships for real time model calibration. Agron. J. 85:140-146.

Keulen, H. van. 1981. Modelling the interaction of water and nitrogen. Plant and Soil 58:205-229.

Koning, A.N.M. 1989a. The effect of temperature on fruit growth and fruit load of tomato. Acta Horticulturae 248:330-336.

Koning, A.N.M 1989b. Development and growth of a commercial grown tomato crop. Acta Horticulturae 260:267-273.

Koning, A.N.M. 1993. Growth of a tomato crop. Acta Horticulturae 328:141-146.

Kooner, K.S. and K.S. Randhawa. 1990. Effects of varying levels and sources of nitrogen on yield and processing qualities of tomato varieties. Acta Horticulturae 267:93-99.

Kropff, M.J., S.E. Weaver, and M.A. Smits. 1992. Use of ecophysiological models for crop-weed interference: Relations amongst weed density, relative time of weed emergence, relative leaf area, and yield loss. Weed Sci. 40:296-301.

Lacheene, Z.A. and A.S. El-Beltagy. 1986. Tomato fruit growth pattern and endogeneous ethylene, indolacetetic acid, and abscisic acid under normal and stress conditions. Acta Horticulturae 190:325-338.

Lambert, D.K. 1990. Risk considerations in the reduction of nitrogen fertilizer use in agricultural production. West. J. Agric. Econ. 15:234-244.

Lapushner. D., R. Frankel, and Y. Fuchs. 1986. Tomato cultivar response to water and salt stress. Acta Horticulturae 190:247-252.

Larouche, R. A. Gosselin, and L. P. Vezina. 1989. Nitrogen concentration and photosynthetic photon flux in greenhouse tomato production: I. Growth and development. J. Am. Soc. Hort. Sci. 114:458-461.

Lee, D.R. 1992. A unidirectional water flux model of fruit growth. Can. J. Bot. 68:1286-1290

Lee, Y.W., M.F. Dahab, and I. Bogardi. 1994. Fuzzy decision making in ground water nitrate risk management. Water. Res. Bull. 30:135-148.

Letey, J., W.M. Jarrel, and N. Valoras. 1982. Nitrogen and water uptake patterns and growth of plants at various minimum solution nitrate concentrations. J. Plant Nutr. 5:73-79.

Lipari, V. , G. Mauromicale, and S. Cosenino. 1988. Comparison of different thermal unit methods for predicting the fruit ripening in tomato. Acta Horticulturae 229:299-305.

Locascio, S.J., G.A. Clark, A.A. Czizinszky, C.D. Stanley, S.M. Olson, F.M. Rhoads, A.G. Smajstrla, G. Vellidis, R.J. Edling, H.Y. Hanna, M.R. Goyal, S. Crossmann, and A.A. Navarro. 1992. Water and Nutrient Requirements for Drip-irrigated Vegetables in Humid Regions. Florida Agric. Exp. Station Southern Coop. Series Bull. 363, Univ. of Florida, Gainesville, FL. 17 pp.

Locascio, S.J., S.M. Olson, F.M. Rhoads, C.D. Stanley, and A.A. Csizinszky. 1985. Water and fertilizer timing for trickle-irrigated tomatoes. Proc. Fla. State Hort. Soc. 98:237-239.

Locascio, S.J. and A.G. Smajstrla. 1989. Drip irrigated tomato as affected by water quantity and N and K application timing. Proc. Fla. State Hort. Soc. 102:307-309.

Locascio, S.J. and A.G. Smajstrla. 1993. Pan evaporation scheduling for drip-irrigation tomato. Proc. Fla. State Hort. Soc. 106:216-218.

Locascio, S.J. and A.G. Smajstrla. 1996. Water application scheduling by pan evaporation for drip-irrigated tomato. J. Am. Soc. Hort. Sci. 121:63-68.

Ludwig, S. 1989. Considerations of risk in production planning. Acta. Horticulturae 248:423-430.

Marcelis, L.F.M. 1993. Simulation of biomass allocation in greenhouse crops - A review. Acta Horticulturae 328:49-67.

Marlowe, G.A., A.J. Overman, and D.J. Schuster. 1983. Growth and development studies of tomato. Proc. Fla. State Hort. Soc. 96:103-207.

Masson, J., N. Tremblay, and A. Gosselin. 1990. Effets de la fertilisation azotee sur la croissance de transplants de tomatote et de laitue cultives en plateaux multicelllaires avec ou sans eclairage d'appoint. Can. J. Plant Sci. 70:1199-1205.

May, D.M. and J. Gonzales. 1994. Irrigation and nitrogen management as they affect fruit quality and yield of processing tomatoes. Acta Horticulturae 376:227-234.

Maynard, D.N. 1992. Vegetable variety trial results in Florida for 1991. Florida Agric. Exp. Station Circ. S-384. 70 pp.

Maynard, D.N. 1993. Vegetable variety trial results in Florida for 1992. Florida Agric. Exp. Station Circ. S-389. 68 pp.

Maynard, D.N. 1994. Vegetable variety trial results in Florida for 1993. Florida Agric. Exp. Station Circ. S-392. 77 pp.

Maynard, D.N. and G.J. Hochmuth. 1995. Vegetable Production Guide for Florida. SP 170. Florida Coop. Ext. Serv. Univ. of Florida, Gainesville, FL.

Maynard, D.N. and T.K. Howe. 1995. Vegetable variety trial results in Florida for 1994. Florida Agric. Exp. Station Circ. S-396. 78 pp.

McNeal, B.L., J.M.S. Scholberg, J.W. Jones, C.D. Stanley, A.A. Csizinszky, and T.A. Obreza. 1995. Application of a greenhouse tomato-growth model (TOMGRO) to field-grown tomato. Soil Crop Sci. Soc. Fla. Proc. 54:86-93

McNeal, B.L., C.D. Stanley, W.D. Graham, P.R. Gilreath, D. Downey, and J.F. Creighton. 1994. Nutrient-loss trends for vegetable and citrus fields in West-Central Florida: I. Nitrate. J. Env. Qual. 24:95-100

Melton, R.R. and R.J. Dufault. 1991. Tomato seedling growth, earliness, yield, and quality following pretransplant nutritional conditioning and low temperatures. J. Am. Soc. Hort. Sci. 116:421-425.

Mengel , K. and E.A. Kirkby. 1987. Principles of Plant Nutrition. Intern. Potash Inst. Bern, Switzerland.

Meurs, W. T. M. and C. Stanghellini. 1992. Environmental control of a tomato crop using a tranpiration model. Acta Horticulturae 303:23-31.

Michelakis, N.G. and K.S. Chartzoulakis. 1988. Water consumptive use of greenhouse tomatoes as related to various levels of soil potential under drip irrigation. Acta Horticulturae 228:127-136.

Millar, A.A. and E.N. Choudhurry. 1980. A model to define operational irrigation frequency for maximum yield of crops. Turrialba 30:391-398.

Miller, R.J., D.E. Rolston, R.S.Rauschkolb, and D.W. Wolfe. 1981. Labeled nitrogen uptake by drip-irrigated tomatoes. Agron. J. 73:265-270.

Mitchell, J.P., C. Shennan, and S.R. Grattan. 1991. Developmental changes in tomato fruit composition in response to water deficit and salinity. Physiol. Plant. 83:177-185.

Motta, N. and E. Medina. 1978. Early growth and photosynthesis of tomato (Lycopersicum esculentum L.) under nutritional deficiencies. Turrialba 28:135-141.

Nassar, H.H. 1986. Effects of planting pattern, plant population and nitrogen level on yield and quality of tomato. Acta Horticulturae 190:435-442.

National Agricultural Statistics Service. 1993. Agricultural Statistics 1993. United States Government Printing Office, Washington D.C.

Navarro, A.A. and S.J. Locascio. 1971. Influence of population density, row arrangement and fertilizer rate on the single-harvest yield of fresh-market tomatoes. Proc. Fla. State Hort. Soc. 129-131.

Nicola, S. and L. Basoccu. 1994. Nitrogen and N,P,K relation affect tomato seedling growth, yield and earliness. Acta Horticulturae 357:95-102.

Obreza, T.A., D.J. Pitts, R.J. McGovern, and T.H. Spreen. 1996. Deficit irrigation of micro-irrigated tomato affects yield, fruit quality, and disease severity. J. Prod. Agric. (submitted).

Olson, S.M. 1989. Pruning method effects on yield, fruit size, and percentage of marketable fruit of 'Sunny' and 'Solarset' tomatoes. Proc. Fla State Hort. Soc. 102: 324-326.

Olson, S.M. and F.M. Rhoads. 1992. Effect of water quantity on fall tomato production in North Florida. Proc. Fla. State Hort. Soc. 105:334-336.

Olson, S.M. and J.M. Snell. 1990a. Tomato variety evaluation 1982-1988. North Fla. Res. and Educ. Center Research Report Number 90-10, IFAS, Univ. of Florida, Quincy, FL. 11 pp.

Olson, S.M. and J.M. Snell. 1990b. Tomato cultivar evaluation spring 1989. North Fla. Res. and Educ. Center Research Report Number 90-19, IFAS, Univ. of Florida, Quincy, FL. 3 pp.

Olson, S.M. and J.M. Snell. 1991. Tomato cultivar evaluation spring 1990. North Fla. Res. and Educ. Center Research Report Number 91-10, IFAS, Univ. of Florida, Quincy, FL. 2 pp.

Peirce, L. C. 1987. Vegetables: Characteristics, Production, and Marketing. John Wiley and Sons, New York, NY. 433 pp.

Penning de Vries, F.W.T. and C.J.T Spitters. 1990. The potential for improvement in crop yield simulation. p. 123-140. In R.C. Muchhow and J.A. Bellamy. (eds.) Climatic Risk in Crop Production, Models and Management for the Semiarid Tropics and Subtropics. CAB, Wallingford, U.K.

Perniola, M, A.R. Rivelli, and V. Candido. 1994. Yield response to water and stress indexes on tomato. Acta Horticulturae 376:215-225.

Persaud, N., S.J. Locascio, and C.M. Geraldson. 1976. Effect of rate and placement of nitrogen and potassium on yield of mulched tomato using different irrigation methods. Proc. Fla. State Hort. Soc. 89:135-138.

Persaud, N., S.J. Locascio, and C.M. Geraldson. 1977. Influence of fertilizer rate and placement and irrigation method on plant nutrient status, soluble salt and root distribution of mulched tomato. Soil Crop Sci. Soc. Fla. Proc. 36:121-125.

Phene, C.J., R.L. McCormick, and J.M. Miyamoto. 1985. Evapotranspiration and crop coefficient of trickle-irrigated tomatoes. p. 823-831. In Proceedings 3 rd Drip/Trickle Irrigation Congress, Fresno, CA.

Picken, A.J.F., K. Stewart, and D. Klapwijk. 1986. Germination and vegetative development. p. 111-166. In J.G.Atherton and J. Rudich (eds.) The Tomato Crop, A Scientific Basis for Improvement, Chapman and Hall, London, U.K..

Pitts, D.J., and G.A. Clark. 1991. Comparison of drip irrigation to subirrigation for tomato production in Southwest Florida. Appl. Eng. Agric. 7:177-184.

Pitts, D.J., G.A. Clark, J. Alvarez, P.H. Everett, and J.M. Grimm. 1988. A comparison of micro to subsurface irrigation of tomatoes. Proc. Fla. State Hort. Soc. 101:393-397.

Pitts, D.J. and T.A. Obreza. 1996. Optimizing microirrigation and land allocation for fresh market tomatoes with water supply restraints. Trans. Am. Soc. Agric. Engr. (ASAE) (submitted).

Pitts, D.J., Y.J. Tsai, D.L. Myhre, and T.A. Obreza. 1991. Irrigation frequency and depth to the water table effects on drip irrigated tomatoes. Soil Crop Sci. Soc. Fla. Proc. 50:12-17.

Portas, C.A.M. and J.J.F.B. Dordio. 1980. Tomato root systems, a short review with reference to tomatoes for processing. Acta Horticulturae 100:113-124.

Prevatt, J.W. and P.H. Everett. 1990. An empirical examination of tomato yield response to fertilizer. Soil Crop Sci. Soc. Fla. Proc. 49:57-59.

Quaglietta-Chiaranda, F. and G. Zerbi. 1981. Effect of irrigation regime on yield and water consumption of greenhouse tomato grown in lysismeters. Acta Horticulturae119:179-190.

Rhoads, F.M. 1990. Irrigation use by mulched staked tomatoes in North Florida. North Fla. Res. and Educ. Center, Quincy Res. Rpt. 90-17. 14 pp.

Rhoads, F.M. and S.M. Olson. 1992. Irrigation of fall tomato in North Florida. North Fla. Res. and Educ. Center, Quincy Res. Rpt. 92-3. 9 pp.

Rhoads, F.M., S.M. Olson, G.J. Hochmuth, and E.A. Hanlon. 1996. Yield and petiole-sap nitrate of tomato with N rates applied preplant or injected. Soil Crop Sci. Soc. Fla. Proc. 55 (in press).

Rhoads, F.M., S.M. Olson, and A. Manning. 1988. Nitrogen fertilization of staked tomatoes in North Florida. Soil Crop Sci. Soc. Fla. Proc. 47:42-44.

Richards, D., F.H. Goubran, and K.E. Collins. 1979. Root-shoot equilibria in fruiting tomato plants. Ann. Bot. 43:401-404.

Rick, C.M. 1978. The tomato. Sci. Amer. 239:66-77.

Ritchie, J.T. 1991. Specification of the ideal model for predicting yields. p. 97-122. In R.C. Muchow and J.A. Bellamy (eds.) Climatic Risk in Crop Production Models for the Semiarid Tropics and Subtropics, CAB, Wallingford, U.K.

Ritchie, J.T. and D.S. Nesmith. 1991. Temperature and crop development. In J. Hanks and J.T. Ritchie (eds.). Modeling Plant and Soil Systems. Am. Soc. Agron. Series No. 31. Am. Soc. Agron. , Crop Sci. Soc. Am, and Soil Sci.Soc. Am., Madison, WI.

Romisio, G.B. A. and M.G.C. Churata-Masca. 1992. Water requirement and crop coefficient for processing tomatoes. Acta Horticulturae 301:165-169.

Rudich, J. and U. Luchinsky. 1986 p. 167-239. In J.G. Atherton and J. Rudich (eds.) The Tomato Crop, A Scientific Basis for Improvement. Chapman and Hall, London, U.K.

Ruff, M.S., D.T. Krizek, R.M. Mirecki, and D.W. Inouye. 1987. Restricted root zone volume: Influence on growth and development of tomato. J. Am. Soc. Hort. Sci. 112:763-769.

Sammis, T.W. and I.P. Wu. 1986. Fresh market tomato yields as affected by deficit irrigation using a micro-irrigation system. Agric. Water Manage. 12:117-126.

Sanders, D.C., T.A. Howell, M.M.S. Hile, L. Hodges, D. Meek, and C.J. Phene. 1989a Yield and quality of processing tomatoes in response to irrigation rate and schedule. J. Am. Soc. Hort. Sci. 114:904-908.

Sanders, D.C., T.A. Howell, M.M.S. Hile, L. Hodges, and C.J. Phene. 1989b. Tomato root development affected by travelling trickle irrigation rate. HortSci. 24:930-933.

Scholberg, J.M.S. 1987. Tomato Production in the Tropics. Bachelors Thesis, Intern. Agric. College, Deventer, The Netherlands.

Scholberg, J.M.S. 1992. Irrigation Method, Water Quantity, and Salinity Effects on the Growth of Bean and Tomato. Masters Thesis, Univ. of Florida, Gainesville, FL.

Scholberg, J.M.S. 1994. Initial modifications of CROPGRO to develop a tomato growth routine. Compiled results of growth studies and parameter estimations. Progress report. Soil & Water Sci. Dept., Univ. of Florida, Gainesville, FL. 76 pp.

Sinclair, T.R. J.M. Benett, and K.J. Boote. 1993. Leaf nitrogen content, photosynthesis and radiation use efficiency in peanut. Peanut Sci. 20:40-43.

Singh.S.D., Singh,Y.V., and R.C. Bhandari. 1989. Tomato yield as related to drip lateral spacing and fertilizer application on total and wetted area basis. Can. J. Plant Sci. 69:991-999.

Smajstrla, A.G. and S.J. Locascio. 1990. Irrigation scheduling of drip irrigated tomato using tensiometers and pan evaporation. Proc. Fla. State Hort. Soc. 103:88-91.

Smajstrla, A.G. and S.J. Locascio. 1994. Irrigation cutback effects on drip-irrigated tomato yields. Proc. Fla. State Hort. Soc. 107:113-118

Smajstrla, A.G. and S.J. Locascio. 1996. Tensiometer-controlled drip irrigation scheduling of tomato. Appl. Eng. Agric. 12: (in press).

Smart, D.R and A.J. Bloom. 1988. Kinetics of ammonium and nitrate uptake among wild and cultivated tomatoes. Oecologia 76:336-340.

Smith, S.A. and T.G. Taylor. 1994. Production cost for selected vegetables in Florida. Coop. Ext. Serv. Circ. 1146, Univ. of Florida, Gaineville, FL. 66 pp.

Smuckers, A.J.M. 1984. Carbon utilization and losses by plant root systems. p. 27-47. In S.A. Barber and D.R. Bouldwin (eds.) Roots, Nutrient and Water Influx, and Plant Growth. Am. Soc. Agron. Special Publication No. 49, Soil Sci. Soc. Am., Crop Sci.Soc. Am., and Am. Soc. Agron., Madison, WI.

Stanley. C.D. and G.A. Clark. 1995. Effect of reduced water table and fertilizer levels on subirrigated tomato production. Trans. Am. Soc. Agric. Engr. (ASAE) 11: 385-388.

Stark, J.C., W.M. Jarell, J. Letey, and N. Valoras. 1983. Nitrogen use efficiency of trickle-irrigated tomatoes receiving continuous injection of N. Agron. J. 75:672-676.

Stoffella, P.J. 1983. Root morphological characteristics of field-grown tomatoes. HortSci. 18:70-72.

Suniaga Quijada, J., M. Bonafous, and. Y. Dumas. 1992. Growth and development of young tomato plants under nitrogen deficiency. Acta Horticulturae 301:159-164.

Sweeney, D.W., D.A. Graetz, A.B. Bottcher, S.J. Locascio, and K.L. Campbell. 1987. Tomato yield and nitrogen recovery as influenced by irrigation method, nitrogen source, and mulch. HortSci. 22:27-29.

Tan, C.S. 1988. Effects of soil moisture stress on leaf and root growth of two processing tomatoes. Acta Horticulturae 228:291-298.

Tan, C.S. 1993. Tomato yield-evaporation relationships. Seasonal canopy temperature and stomatal conductance as affected by irrigation. Can. J. Plant Sci. 73:257-264.

Tan, C.S., A. Cornelisse, and B.R. Buttery. 1981. Transpiration, stomatal conductance, and photosynthesis of tomato plants with various proportions of the root system supplied with water. J. Amer. Soc. Hort. Sci. 106:147-151.

Tan, C.S. and J.M. Fulton. 1985. Water uptake and root distribution by corn and tomato at different depths. HortSci. 20:686-688.

Tanaka, A., K. Fujita, and K. Kikuchi. 1974. Nutro-physiological studies on the tomato plant. III. Photosynthetic rate of individual leaves in relation to the dry matter production of plants; IV. Source-sink relationship and structure of the source-sink unit. Soil Sci. Plant Nutr. 20:173-183; 305-315.

Tennant, D. 1975. A test of a modified intersect method of estimating root length. J. Ecol 63:995-1001.

Thompson, A.C., H.C. Lane, J.W. Jones, and J.D. Hesketh. 1976. Nitrogen concentrations of cotton leaves, buds, and bolls in relation to age and nitrogen fertilization. Agron. J. 68:617-621.

Tindall, J.A., R.B. Beverly, and D.E. Radcliffe. 1991. Mulch effect on soil properties and tomato growth using micro-irrigation. Agron. J. 83:1028-1034.

United States Department of Agriculture. 1984. United States Standards for Grades of Fresh Tomatoes. USDA, Washington D.C.

Valenzuela, J.L., A. Sanchez, F.A. Lorente, A. del Rio, and L. Romero. 1990. Does N directly influence carbohydrates and pigments in tomato and cucumber? Acta Horticulturae 287:477-483.

Varga, A. and J. Bruinsma. 1986. Tomato. p. 461-481. In S.P. Monselise (ed.). CRC Handbook of Fruitset and Development. Chemical Rubber Company, Boca Raton, FL.

Vavrina, C.S. 1991. Effect of transplant age on tomato production. Proc. Fla. State. Hort. Soc. 104:225-226.

Vaysse, P. 1981. Water stress response of tomato under protected culture on drip irrigation. Acta Horticulturae 119:285-291.

Vellidis, G., A.G. Smajstrla, and F.S. Zazueta. 1988. Water use of drip irrigated tomatoes under high water table conditions. Proc. Fla. State Hort. Soc. 101:376-380.

Vellidis, G., A.G. Smajstrla, and F.S. Zazueta. 1990. Soil water distribution and extraction patterns of drip-irrigated tomatoes above a shallow water table. Am. Soc. Agric. Engr. (ASAE) 33:1525-1530.

Vinten, A., S. Shalhavet, A. Meiri, and J. Peretz. 1985. Water and leaching requirements of industrial tomatoes irrigated with brackish water. Irrig. Sci. 7:13-25.

Voogt, W. 1993. Nutrient uptake of year round tomato crops. Acta Horticulturae 339:99-112.

Wien, H.C. and P.L. Minotti. 1987. Growth, yield, and nutrient uptake of transplanted fresh-market tomatoes as affected by plastic mulch and initial nitrogen rate. J. Am. Soc. Hort. Sci 112:759-763.

Wien, H.C., P.L. Minotti, and V.P. Grubinger. 1987. Polyethylene mulch stimulates early root growth and nutrient uptake of transplanted tomatoes. J. Am. Soc. Hort. Sci. 118:207-211.

Wilkerson, G.G., J.W. Jones, K.J. Boote, K.T Ingram, and J.W. Mishoe. 1983. Modeling soybean growth for crop management. Am. Soc. Agric. Engr (ASAE) 26:63-73.

Wilson, L.T., R. Tennyson, A.P. Gutierrez, and F.G. Zalom. 1987. A physiological based model for processing tomatoes:crop and pest management. Acta Horticulturae 200:125-132.

Wolf, S., J. Rudich, A. Marani, and Y. Rekah. 1986. Predicting harvesting date of processing tomatoes by a simulation model. J. Am. Soc. Hort. Sci. 111:11-16.

Yrisarry, J.J.B., M.H.P. Losada, A. Rodriquez del Ricon. 1993. Response of processing tomato to three different levels of water and nitrogen applications. Acta Horticulturae 335:149-156.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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